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Climate policy under factor mobility: A (differentiated) case for capital taxation[☆]

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ABSTRACT

In a general equilibrium model with two periods and a finite fossil resource, I analyze the non-cooperative climate policies of symmetric countries that are in competition for mobile factors of production (capital and fossil energy). The paper shows that countries that want to slow down climate change but are also concerned about tax revenues from mobile tax bases have a rationale to supplement environmental taxes on fossil fuels with source-based capital taxes (or subsidies). More specifically, countries find it beneficial to subsidize capital in period one and tax it in period two. The first-period subsidy on capital facilitates a higher environmental tax by counteracting its adverse effects, and increases national and global welfare in equilibrium. By contrast, the capital tax in period two induces inter- and intratemporal distortions that lead to lower welfare. The rate of resource extraction is inefficiently high in equilibrium, no matter which tax portfolio is at the governments' disposal. Furthermore, unintended ('Green Paradox') effects of demand-side policies are shown to arise even in general equilibrium with factor mobility. Finally, factor mobility does not necessarily lead to a higher rate of extraction and lower welfare compared to autarky.

1. Introduction

When production factors such as capital or fossil fuels are mobile between countries, governments have to balance a number of strategic concerns. If they want to increase tax revenues and domestic economic output, they can distort the allocation of

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production factors in their favour by lowering taxes on these factors (or even putting a subsidy on them).[1] In the case of fossil fuels and capital, a decrease in taxes on one factor (say, fossil fuels) increases not just demand for that factor, but also demand for the other factor, as capital and fossil energy are generally found to be complements in production. If governments additionally want to address the externalities of fossil fuels, they have to increase rather than decrease taxes on these two inputs to make their use less attractive, and take into account that their mitigation efforts might be partially offset in other countries through 'carbon leakage'. The trade-off for governments becomes even more complex when considering that climate change and the extraction of fossil resources are intertemporal problems, and well-intentioned policies to address these problems can have unintended effects (cf. 'Green Paradox' as postulated by Sinn, 2008).

This paper asks how benevolent governments best solve these trade-offs in the 'second best', i.e. when they are constrained by tax competition. How should they set environmental taxes when their policies have an influence not only on environmental damage in the form of global warming but also on the location of mobile tax bases? Do countries have incentives to supplement environmental taxes with capital taxes or subsidies, given that the markets for capital and fossil fuels are intertwined through the complementarity of capital and fossil energy in production? And are they better or worse off in equilibrium when they do so?

To answer these questions, I develop a general equilibrium model with two mobile and complementary factors of production (capital and fossil fuels). To capture the dynamics of climate externalities, the model has two periods, at the end of which a finite stock of coal, oil and natural gas is fully extracted. The use of fossil fuels in production gives rise to greenhouse gas (GHG) emissions. The governments of two symmetric countries non-cooperatively maximize their populations' lifetime utility by choosing from a set of environmental taxes on fossil fuels and source-based capital taxes. These governments are concerned with attracting mobile factors of production to increase tax revenues, while at the same time slowing down the rate of extraction of fossil resources. The main findings of the paper are as follows.

First, there is a rationale for welfare-maximizing governments to implement capital taxes as a supplement to environmental taxes on fossil energy (henceforth referred to as 'resource taxes'). More specifically, governments have an incentive to subsidize capital investment in period one and tax it in period two. In this way, the optimal time profile in the second best for implementing capital taxes is exactly the opposite of that of resource taxes. The intuitive explanation for negative capital taxes in the first period and positive capital taxes in the second is as follows: While the resource tax in the first period leads to capital and resource flight, the capital subsidy reallocates both capital and resources back to the home country. It balances the marginal income loss from resource taxation when the capital tax is marginally increased (which leads resource use in the tax-increasing country to go down) and the marginal income gain from having to subsidize less domestic capital. Similarly, the capital tax in the second period offsets marginal income losses and marginal income gains from resource and capital taxation, and it allows countries to reduce subsidy payments on resource use in the second period, because it induces resource flight to other countries. (Note that the negative resource tax in the second period discourages resource extraction in the first period.)

Second – and this is the main contribution of the paper – the use of a period-one capital subsidy in addition to resource taxes leads to higher welfare in equilibrium than any other tax portfolio. Furthermore, the greater the elasticity of substitution between capital and resources in production, the higher this gain in welfare is. The intuitive explanation is that the capital subsidy in the first period is non-distortionary, i.e. it does not impose any net externalities on other countries. At the same time, it facilitates a higher resource tax in the first period because it is able to offset part of the negative effect of that tax by retaining domestic investment. The second-period capital tax, by contrast, induces several distortions, both atemporally and intertemporally, by influencing resource tax revenues in both periods and distorting the consumption-savings margin. Therefore, adding it to the portfolio of (first- and second-period) resource taxes and the first-period capital subsidy is Pareto inferior to using only these three instruments. To the best of my knowledge, this is the first paper in the tax competition literature that provides a welfare comparison of different tax regimes in general equilibrium. Although the traditional capital tax competition literature restricts itself to examining one-instrument policies, the complementarity between production factors makes the welfare effects induced by various combinations of tax policy in the second best a compelling subject of study. While one would expect that more instruments will imply lower aggregate welfare in a Nash equilibrium because each instrument adds additional distortions, I show that this is not necessarily true.

Finally, the paper contains a number of ancillary results. The first of these is that unilateral increases in resource or capital taxes cause not just *intra*temporal leakage of fossil fuels and thus emissions, but also *inter*temporal leakage. For the assumed positive capital supply elasticity, a higher future resource tax in one country induces higher resource extraction in the present, confirming the existence of Green Paradox effects, as found in partial equilibrium models (Sinn, 2008; Sinclair, 1992, 1994) and in general equilibrium models (van der Meijden et al., 2015; van der Ploeg, 2016), even in the case of factor mobility. Unilateral increases in the first-period capital tax are neutral with respect to the rate of resource extraction but cause an intratemporal reallocation of capital investment and resource use. By contrast, higher *future* capital taxes in one country either speed up or slow down extraction, depending on, among other factors, the degree of complementarity between capital and resources in production. If, for instance, capital and resources can easily be substituted, an increase in the future capital tax leads to greater resource use in the future and thus less resource use in the present.

[1] Such competition for mobile production factors is evidenced by, e.g., the declining statutory corporate income tax (CIT) rates in most regions of the world. For example, the average CIT rate in EU countries dropped from 35.5% to 24.2% between 1997 and 2007 (KPMG, 2007).

The second ancillary result is that resource extraction in period one and thus environmental damage is inefficiently high in the Nash equilibrium, no matter which tax portfolio is at the governments' disposal. This is little surprising and complements earlier findings in the literature (described in detail in the next section). The last result states that factor mobility does not necessarily lead to a decrease in welfare in equilibrium compared to autarky, although additional private income externalities arise from the taxation of mobile tax bases (capital and resources) and go in the same direction as the environmental externality, which is also present under autarky. However, due to general equilibrium and world market effects, environmental externalities imposed on other countries in the Nash equilibrium do not have the same size under factor mobility and under autarky. The fact that factor mobility is not necessarily detrimental in terms of global welfare compared to autarky is a new finding in the literature for the assumed symmetry of countries.

2. Related literature

This paper bridges the gap between two strands in the literature: the literature on resource economics, which analyzes the *intertemporal* allocation of non-renewable resources, and the literature on tax competition, which is concerned with the *static* allocation of production factors and the efficiency of decentralized policy-making in the presence of interjurisdictional spillovers.

The paper contributes to the latter strand in the literature, pioneered by Zodrow and Mieszkowski (1986) and Wilson (1986), by introducing a finite stock of resources and allowing for different degrees of complementarity between capital and resources in a general equilibrium framework. One of the first contributions to this area of research in the context of environmental policy is Oates and Schwab (1988). They find that decentralized policy-making is efficient if there are no pollution spillovers across jurisdictions and first-best tax instruments are available. Ogawa and Wildasin (2009) confirm this result for transboundary pollution, given that emissions are proportional to capital and there is a fixed supply of capital. However, under their assumptions, any tax rate is efficient and so is the tax rate in the Nash equilibrium. Eichner and Runkel (2012) endogenize capital supply, and thus emissions, in the same model framework and conclude that the Nash equilibrium brings about inefficiently low capital taxes. While the focus of their paper is on the role of capital supply elasticity and assumes a one-to-one relationship between capital and emissions, the present paper is concerned with the role of the elasticity of substitution between capital and resources in production. Fell and Kaffine (2014) also reject the efficiency result obtained in Ogawa and Wildasin (2009) in a more general model that allows for capital retirement and abatement activities. Withagen and Halsema (2013) employ a tax competition framework but reverse the conventional timing of decisions such that households anticipate government policies (and not the other way round) when deciding about savings. They find a potential race to the top in environmental regulation. Rauscher employs similar but static models of interjurisdictional factor mobility. In the case of environmental externalities on utility, capital mobility aggravates transboundary pollution problems (Rauscher, 1991, 2000, 2005) and implies inefficiently lax environmental regulations. By contrast, environmental regulation may be inefficiently strict if emission externalities affect capital productivity (Rauscher, 1997a, 1997b). The literature on tax competition has largely ignored intertemporal considerations as discussed in this paper, with the exception of Gross et al. (2017). Furthermore, the literature does not undertake any welfare comparisons between different tax portfolios, which is another contribution of this paper.

The present paper also adds to the resource economics literature, which has mostly focused on single-country models (which can be interpreted as representing the world economy) or comparative static exercises in multi-country models, largely neglecting strategic interaction between countries. Svensson (1984), Marion and Svensson (1984), Elbers and Withagen (1984) and van Wijnbergen (1985) study the welfare effects of oil price increases, of tariffs and subsidies on oil imports and of capital income taxes in models of international trade in the absence of any pollution externalities. Aarrestad (1978) and Farzin (1999) examine the joint determination of optimal savings and resource extraction in a model with an exogenous interest rate and no factor mobility. The rare general equilibrium treatments in this literature include Chiarella (1980), Elbers and Withagen (1984), Hillman and Long (1985) and Golosov et al. (2014). Recently, a new strand has emerged – the literature on the so-called 'Green Paradox', a term coined by Sinn (2008) to define an idea first presented in Sinclair (1992, 1994). This strand studies the effects of taxes on the equilibrium extraction path of a non-renewable resource. The (weak version of the) Green Paradox states that a greening of future tax policies will induce resource owners to speed up resource extraction in the present. My paper is most closely related to van der Meijden et al. (2015) and van der Ploeg (2016). The former finds that the Green Paradox may be mitigated, attenuated or even reversed in general equilibrium, with the most realistic outcome being a weakening of this unintended effect. The latter paper extends the analysis in van der Meijden et al. (2015) by offering a more intuitive interpretation of the comparative statics of first- and second-best climate policies (using duality theory) and by deriving closed-forms solutions for first- and second-best optimal policies. In this paper, I confirm that Green Paradox effects also occur under reasonable assumptions in the presence of factor mobility. In addition, I go one step beyond the analysis in van der Meijden et al. (2015) by deriving the Nash equilibrium tax rates on resources and capital under commitment. Whereas van der Ploeg (2016) allows for asymmetric countries and endogenous resource supply, I consider symmetric countries and exogenous resource supply. Furthermore, van der Ploeg analyzes unilateral second-best policies, whereas I investigate second-best Nash equilibria. Finally, the capital tax in van der Ploeg (2016) is levied on the capital

supply side, while it is levied on the capital demand side in this paper.[2] In contrast to some papers in the Green Paradox literature that allow for an endogenous amount of extraction, I assume that resources will be fully extracted by the end of the time horizon. Further related papers are Eichner and Pethig (2011, 2013) who analyze unilaterally imposed emissions caps in models with two periods and two or three countries but neither include capital as a production input nor an endogenous extraction decision by resource firms. Burniaux and Oliveira Martins (2012) develop a two-region, two-goods general equilibrium framework with international trade and capital mobility to explore the carbon leakage of unilaterally imposed policies.

At the intersection of these two literatures, Franks et al. (2015) model the strategic interactions between two symmetric resource-importing countries and show that competition over carbon taxes Pareto dominates competition over capital taxes because the former is able to capture part of the resource owners' scarcity rent. Tax competition in that model is motivated purely by fiscal concerns, not environmental ones as in my model. Ogawa et al. (2016) show in a static model that, while increased capital mobility increases global production efficiency, the gains from capital market integration accrue only to resource-poor countries.

The papers mentioned above lack at least one of the following features, which are all relevant in the context of climate policy and addressed in the present paper: (1) Non-renewable resources are in finite supply; (2) their use causes environmental externalities; (3) the economy is not a single unit, and decentralized policy-making implies strategic interactions; (4) capital and resources, once they are extracted, are mobile; and (5) factor markets for capital and resources interact with each other because capital and resources can be substituted to some degree, which requires treatment in a general equilibrium framework.

3. The model

The considered economy consists of $n = 2$ symmetric jurisdictions, which can be thought of as sovereign countries.[3] The time horizon of the model comprises two periods, of which the first period can be interpreted as covering the near future (say, the next ten to twenty years), and the second period the time after that. For simplicity, I shall sometimes refer to period one as 'the present' or 'today' and period two as 'the future' or 'tomorrow'. Governments are the strategic agents in the model and play a Nash game over tax rates at the beginning of period one, taking the decisions and reactions of all non-strategic followers, i.e. households and firms, into account.

The model draws on Eichner and Runkel (2012) but differs in two important respects. First, I model production not only in one period. This allows me to capture the effect of current policies on the extraction of fossil resources as well as on savings and thus future consumption. Second, I relax the assumption that emissions are tied one-to-one to capital investment, by introducing non-renewable resources or energy as an explicit production factor, which can be substituted for capital to some degree and whose use gives rise to transboundary and harmful emissions. As a result of this, taxes on capital and taxes on resources can be considered separately. Resources are fully exhausted by the end of the time horizon.

3.1. Production firms

In each country $i = 1, 2$ and each period $t = 1, 2$, a representative firm produces an output good which is taken as the numéraire. Firms in all countries have access to the same production technology. I use k_t^i to denote capital input and r_t^i non-renewable resource (or fossil energy) input in country i in period t. Production in country i in period t amounts to $F^t(k_t^i, r_t^i)$.[4] Production is increasing in both inputs, with decreasing marginal returns ($F_{kk}^t < 0 < F_k^t, F_{rr}^t < 0 < F_r^t$). The cross-partial derivatives are assumed to be positive, $F_{kr}^t > 0$ (though I will sometimes contrast my results with $F_{kr}^t = 0$ to provide more intuition).[5] The larger the cross-derivative, the more complementary (or 'cooperative' in the terminology of Svensson, 1984) are capital and resources in production. I further assume that production exhibits decreasing returns to scale, which implies strictly positive profits.[6]

Capital is traded in a global capital market at the uniform rate ρ_t, while resources, once extracted, are traded in a global resource market at price p_t in period t.[7]

Given that country i levies a source-based, period-specific unit tax κ_t^i on capital and a period-specific unit tax τ_t^i on resource use (referred to as 'environmental' or 'resource' tax), the after-tax profit of the representative firm in country i in period t is given by:

[2] Methodologically, another difference between van der Meijden et al. (2015)/van der Ploeg (2016) and this paper is that their analysis is based on examining equilibria in the resource and final goods markets, whereas I examine equilibria in capital and resource markets. As is standard in the tax competition literature, final goods markets clear in the background of the model through Walras' law.

[3] All results can be generalized to n 'large' countries which are able to influence world market prices.

[4] Production technologies could be the same or different across the two periods.

[5] Note the difference in notation between F_{kr}^2 and $(F_{kr}^2)^2 = F_{kr}^2 \times F_{kr}^2$.

[6] An alternative interpretation is that the production function is linearly homogenous in capital, resources and a fixed factor such as labor and land as, for example, in Hassler and Krusell (2012). Deducting capital and resource costs from profits yields the rent accruing to the fixed factor.

[7] Transport costs of resource trade are assumed to be zero.

$$\pi_t^i = F^t(k_t^i, r_t^i) - (\rho_t + \kappa_t^i)k_t^i - (p_t + \tau_t^i)r_t^i \ . \tag{1}$$

Profit maximization implies that after-tax returns to both factors are equalized across countries in all periods[8]:

$$F_k^t(k_t^i, r_t^i) - \kappa_t^i = \rho_t \ , \quad F_r^t(k_t^i, r_t^i) - \tau_t^i = p_t \ . \tag{2}$$

The positive cross-partial derivatives imply that if the price of one production factor goes up (through an increase in world market prices and/or the domestic tax levied on that factor), not only demand for this factor but also that for the other factor goes down.

3.2. Resource extraction firms

In each country, there is a limited, identical and homogenous stock of non-renewable resources – say coal, oil and gas – which can be extracted at zero cost and will be used as an input to the goods production described above. The resource stock located in country i, Q^i, is managed and fully exploited by a representative resource extraction firm, which supplies a competitive world market with q_1^i units of the resource in the present, and with the remainder, $q_2^i = Q^i - q_1^i$, in the future.[9] In contrast to the production firm, each country's extraction firm faces an intertemporal maximization problem. The net present value of profits is given by[10]:

$$\Pi^i = \Pi_1^i + \frac{\Pi_2^i}{1+\rho_2} = p_1 q_1^i + \frac{p_2 q_2^i}{1+\rho_2} \ . \tag{3}$$

Maximizing (3) subject to the resource constraint and taking world market prices as given implies that the price of the resource rises at a rate equal to the second-period interest rate:

$$p_2 = p_1(1+\rho_2) \ . \tag{4}$$

This equation is the well-known Hotelling's rule, which keeps resource extraction firms in both countries indifferent between extracting today and tomorrow (Hotelling, 1931).

Thus, in this competitive resource market, it is the resource demand that pins down equilibrium extraction as long as equation (4) holds.[11] How much of the global resource stock $Q = \sum_{l=1}^{2} Q^l$ is extracted in the first period depends on the point of intersection of the aggregate first-period inverse (resource) demand schedule and the aggregate second-period inverse demand schedule, with the latter discounted by $1 + \rho_2$. Importantly, this implies that the equilibrium quantity supplied by each resource firm in period one is, in principle, indeterminate. Only *in aggregate* must supply meet demand in each period, i.e. $\sum_{l=1}^{2} q_1^l = \sum_{l=1}^{2} r_1^l$ and $\sum_{l=1}^{2} q_2^l = \sum_{l=1}^{2} r_2^l$, and there is a continuum of supplied quantities that satisfy these equalities.

3.3. Households

Each country i is populated by a representative household, which owns both the production and the extraction firm in its country of origin and thus receives the corresponding profits π_t^i and Π_t^i. Any positive revenues ψ_t^i from the taxation of production inputs are returned in a lump-sum payment to the household in each period:

$$\psi_t^i = \kappa_t^i k_t^i + \tau_t^i r_t^i \ , \tag{5}$$

where ψ_t^i is the sign-unconstrained lump-sum transfer in period t.

First- and second-period consumption, c_1^i and c_2^i, then read:

$$c_1^i = \pi_1^i + \Pi_1^i + \psi_1^i + (1+\rho_1)\overline{k^i} - s^i \ , \quad c_2^i = \pi_2^i + \Pi_2^i + \psi_2^i + (1+\rho_2)s^i \ , \tag{6}$$

where s^i and $\overline{k^i}$ are household i's savings and capital endowment in the first period.

The household receives utility from first- and second-period consumption, but is harmed by pollution from global resource use $r_1 = \sum_{l=1}^{2} r_1^l$ in the first period, $D(r_1)$. One can think here of greenhouse gas emissions from burning fossil fuels in produc-

[8] Note that the profit maximization problem of the firm is static in nature. There are no intertemporal trade-offs for the firm.

[9] None of the results change if I assume that the resource owner herself (the representative household to be described next) manages the resource stock.

[10] The focus of this paper is on demand-side policies, which is why I neglect any taxes on resource extraction, so-called 'severance taxes'. Although some U.S. states rely very heavily on severance taxes, most environmental taxes are energy- or transport-related (EEA, 2000). Furthermore, demand-side policies seem to rank higher on the political agenda than supply-side policies.

[11] As shown by Stiglitz (1976), monopoly pricing yields the same result as competitive markets if resource demand elasticities are the same across periods.

tion.[12] The welfare of the representative household in country i reads:

$$W^i = U(c_1^i) - D(r_1) + \epsilon c_2^i \ , \tag{7}$$

where $\epsilon \le 1$ is the discount factor.[13] U is assumed to be concave and twice differentiable while pollution damages are assumed to be weakly convex ($U'' < 0 < U'$, $D' > 0$, $D'' \ge 0$). The quasi-linear specification of the utility function rules out income effects on first-period consumption. This can be justified by empirical evidence that the substitution effect of a marginal change in the interest rate outweighs the income effect (see, for example, Boskin, 1978, or Gylfason, 1993).

Households choose savings s_i to maximize utility (7) subject to budget constraints (6), taking firm profits, lump-sum transfers and damages as given. From the necessary and sufficient condition for a household maximum (Euler equation),

$$U'(c_1^i) - \epsilon(1 + \rho_2) = 0 \ , \tag{8}$$

we obtain for marginal increases in the interest rates ρ_1, ρ_2 and first-period income π_1^i, Π_1^i or ψ_1^i:

$$\frac{\partial s^i}{\partial \pi_1^i} = \frac{\partial s^i}{\partial \Pi_1^i} = \frac{\partial s^i}{\partial \psi_1^i} = 1 \ , \quad \frac{\partial s^i}{\partial \rho_1} = \overline{k^i} \ , \quad \frac{\partial s^i}{\partial \rho_2} = -\frac{\epsilon}{U''(c_1^i)} \ > \ 0 \ . \tag{9}$$

The first and second equations for (9) state that, starting from a household optimum, any increase in the interest rate, profits or the lump-sum transfer in the first period increases second-period consumption via an associated increase in savings. The third equation implies a positive capital supply elasticity $(\partial s^i/\partial \rho_2)\rho_2/s^i > 0$: when ρ_2 rises, the marginal utility from first-period consumption must rise, by equation (8), entailing lower consumption in period one and higher savings.

3.4. Global markets

Capital is assumed to be perfectly mobile between countries and traded in a global capital market in each period. The equilibrium interest rates ρ_t in these markets are found by equating capital demand by production firms, as described by equation (2), and capital supply by households, as implicitly characterized by equation (8):

$$\sum_{l=1}^{2} k_1^l = \sum_{l=1}^{2} \overline{k^l} \ , \quad \sum_{l=1}^{2} k_2^l = \sum_{l=1}^{2} s^l \ . \tag{10}$$

In contrast to the capital market, the resource market needs not only to equate demand and supply across countries but also across periods. One necessary condition for resource markets to clear is Hotelling's rule, equation (4). The other necessary conditions are:

$$\sum_{l=1}^{2} r_1^l = \sum_{l=1}^{2} q_1^l \ , \quad \sum_{l=1}^{2} r_2^l = \sum_{l=1}^{2} q_2^l \ . \tag{11}$$

Together with the resource constraint for each country, $q_1^i + q_2^i = Q^i$, these two equations yield:

$$\sum_{l=1}^{2} r_1^l + \sum_{l=1}^{2} r_2^l = Q \ . \tag{12}$$

The resource demand functions on the left-hand side of equation (11) are implicitly given by equation (2), whereas the supply functions on the right-hand side are indeterminate as long as Hotelling's rule holds. Hotelling's rule and equations (10) and (11) jointly determine the equilibrium world market prices ρ_1, ρ_2, p_1 and p_2 as functions of the tax rates $\tau_1^i, \kappa_1^i, \tau_2^i$ and κ_2^i in both countries.

Note that the equilibrium levels of capital and resources used in production are determined by the first-order conditions of profit maximization (2), Hotelling's rule (4), the Euler equation (8) and the prices implied by the market-clearing conditions (10)–(11), and can thus also be expressed as functions of $\tau_1^i, \kappa_1^i, \tau_2^i$ and κ_2^i in both countries.

[12] I neglect damages in the second period in order to focus on the effects of environmental and fiscal policy on the rate of extraction (which is equivalent to first-period extraction). This assumption can be defended on two grounds. First, the natural decay and removal rate of greenhouse gases from the atmosphere is relatively small over a short time horizon. Consequently, as resources are fully extracted in this model, the damage in the second period is simply a function of Q and thus a constant. Second, there are benefits to slowing down the rate of extraction and thus the rate of emissions. In particular, this buys countries time to develop more effective adaptation strategies and better mitigation technologies. I thank an anonymous reviewer for making the latter point.

[13] In contrast to Eichner and Runkel (2012), I do not assume that a physical public good is provided because this would only change the level of the lump-sum transfer but not any of the tax rates considered here.

4. Comparative statics of unilateral tax policies

Having characterized all demand and supply schedules as well as the equilibrium in all markets, we can now compute the effects of unilateral marginal tax increases on prices, the allocation and accumulation of capital, and the allocation of resources across countries and across periods. This is important for gaining an understanding of the effects that taxes, in particular capital taxes, have, what sign they have in equilibrium and why governments may find it beneficial to use them.

To derive the comparative statics, we totally differentiate equation (2) for all $i=1,2$ and all $t=1,2$ as well as (4), and insert them into the differentiated conditions (10) and (12), using equation (9). The comparative statics with respect to second-period tax rates can be regarded as announcement effects. Starting from a symmetric equilibrium in which $k_1^i = \overline{k^i}$, $k_2^i = s^i = s$ and $q_t^i = r_t^i$ for all $i=1,2$ and $t=1,2$ hold, we arrive at the following results (derived in Appendix A.1) – first for resource taxes, then for capital taxes.[14]

4.1. Resource taxes

For unilateral marginal increases in the resource taxes τ_1^i (left-hand side of the following equations) and τ_2^i (right-hand side), the following holds (the arguments of all functions are suppressed for notational convenience):

$$\frac{\partial \rho_1}{\partial \tau_1^i} = -\frac{(1+\rho_2)F_{kr}^1 \Theta}{2\Delta} < 0\,, \qquad \frac{\partial \rho_1}{\partial \tau_2^i} = \frac{F_{kr}^1 \Theta}{2\Delta} > 0\,, \tag{13a}$$

$$\frac{\partial \rho_2}{\partial \tau_1^i} = \frac{(1+\rho_2)(F_r^1 F_{kk}^2 - F_{kr}^2)}{2\Delta} > 0\,, \qquad \frac{\partial \rho_2}{\partial \tau_2^i} = \frac{F_{kr}^2 - F_r^1 F_{kk}^2}{2\Delta} < 0\,, \tag{13b}$$

$$\frac{\partial p_1}{\partial \tau_1^i} = \frac{F_r^1 F_{kr}^2 + \Gamma_2 \frac{\partial s}{\partial \rho_2} - p_1 \Phi - F_{rr}^2}{2\Delta} < 0\,, \qquad \frac{\partial p_1}{\partial \tau_2^i} = \frac{F_{rr}^1 \Theta}{2\Delta} < 0\,, \tag{13c}$$

$$\frac{\partial p_2}{\partial \tau_1^i} = \frac{(1+\rho_2)(F_r^1 F_{kr}^2 + \Gamma_2 \frac{\partial s}{\partial \rho_2} - F_{rr}^2)}{2\Delta} < 0\,, \qquad \frac{\partial p_2}{\partial \tau_2^i} = \frac{F_{rr}^1 (1+\rho_2)\Theta - p_1 \Phi}{2\Delta} < 0\,, \tag{13d}$$

where $\Gamma_1 = F_{kk}^1 F_{rr}^1 - (F_{kr}^1)^2 > 0$, $\Gamma_2 = F_{kk}^2 F_{rr}^2 - (F_{kr}^2)^2 > 0$, $\Omega = F_{rr}^1(1+\rho_2) + F_{rr}^2 < 0$, $\Phi = F_r^1 F_{kk}^2 - F_{kr}^2 < 0$, $\Lambda = -\partial s/\partial \rho_2 [\Gamma_2 + F_{rr}^1 (1+\rho_2) F_{kk}^2] < 0$, $\Theta = F_{kk}^2 \partial s/\partial \rho_2 - 1 < 0$, and $\Delta = \Omega + p_1 \Phi + \Lambda - F_r^1 F_{kr}^2 < 0$.[15]

Marginal increases in any of the two tax rates lower the world market price for the resource in the respective periods because they curb contemporaneous demand. At the same time, they also lower world market prices in the other period in order to equilibrate the market. As can be seen from equation (13b), a marginal increase in τ_1^i leads to a steeper price path for the resource, as measured by $1+\rho_2$. This is, however, not associated with lower resource extraction in period two and higher resource extraction in period one, as one would expect, because the market prices are endogenous. As we shall see shortly, an increase in τ_1^i is associated with *less* resources being used in period one and *more* being used in period two. The opposite holds for a marginal increase in τ_2^i.

In other words, a marginal increase in τ_1^i (or a marginal decrease in τ_2^i) raises ρ_2 for two reasons. On the one hand, it negatively affects resource use in the first period and thus production, as we will see below. Lower production goes hand-in-hand with lower income and implies lower savings and thus lower capital supply in the second period, which increases ρ_2. This capital supply effect is present even under a purely substitutive production technology, $F_{kr}^2 = 0$. On the other hand, there is a capital demand effect on ρ_2 through the assumed complementarity of resources and capital in production. This effect goes in the same direction as the capital supply effect: the increase in second-period resource use induced by the increase in τ_1^i shifts the demand for capital in period two upwards, which also increases ρ_2.

Regarding the effects on the first-period interest rate ρ_1, a marginal increase in τ_1^i or a marginal decrease in τ_2^i have the same qualitative effects: they lower ρ_1, because they shift, for $F_{kr}^1 > 0$, the first-period demand curve for capital downwards as fewer resources are demanded and used in period one.

We denote the total amount of resources used in production in the two countries in period t by $r_t = \sum_{l=1}^{2} r_t^l$ and obtain for resource use in the tax-increasing country $i=1,2$, the other country $j \neq i$ and in aggregate the following:

$$\frac{\partial r_1^i}{\partial \tau_1^i} = \frac{F_{kk}^1 \Delta - (1+\rho_2)\Gamma_1 \Theta}{2\Gamma_1 \Delta} < 0\,, \qquad \frac{\partial r_1^i}{\partial \tau_2^i} = \frac{\Theta}{2\Delta} > 0\,, \tag{14a}$$

[14] As mentioned in Section 3.2, asymmetric extraction across countries is possible and would imply asymmetric resource incomes across countries in the first period. However, I focus on a symmetric equilibrium where players use the same strategy, i.e. the same tax rates. Identical tax rates, however, can only be a best response if extraction occurs symmetrically such that $q_t^i = r_t^i$ and $s^i = k_2^i$.

[15] With decreasing returns to scale in production as assumed, Γ_t is strictly positive for all $t=1,2$. Constant returns to scale would imply $\Gamma_t = 0$.

$$\frac{\partial r_1^j}{\partial \tau_1^i} = -\frac{F_{kk}^1 \Delta + (1+\rho_2)\Gamma_1 \Theta}{2\Gamma_1 \Delta} > 0 \,, \quad \frac{\partial r_1^j}{\partial \tau_2^i} = \frac{\Theta}{2\Delta} > 0 \,, \tag{14b}$$

$$\frac{\partial r_1}{\partial \tau_1^i} = -\frac{(1+\rho_2)\Theta}{\Delta} < 0 \,, \quad \frac{\partial r_1}{\partial \tau_2^i} = \frac{\Theta}{\Delta} > 0 \,, \tag{14c}$$

$$\frac{\partial r_2^i}{\partial \tau_1^i} = \frac{(1+\rho_2)\Theta}{2\Delta} > 0 \,, \quad \frac{\partial r_2^i}{\partial \tau_2^i} = \frac{F_{kk}^2 \Delta - \Gamma_2 \Theta}{2\Gamma_2 \Delta} < 0 \,, \tag{14d}$$

$$\frac{\partial r_2^j}{\partial \tau_1^i} = \frac{(1+\rho_2)\Theta}{2\Delta} > 0 \,, \quad \frac{\partial r_2^j}{\partial \tau_2^i} = -\frac{F_{kk}^2 \Delta + \Gamma_2 \Theta}{2\Gamma_2 \Delta} > 0 \,, \tag{14e}$$

$$\frac{\partial r_2}{\partial \tau_1^i} = \frac{(1+\rho_2)\Theta}{\Delta} > 0 \,, \quad \frac{\partial r_2}{\partial \tau_2^i} = -\frac{\Theta}{\Delta} < 0 \,. \tag{14f}$$

Unilateral increases in period-t resource taxes have unambiguous and intuitive effects on resource use, as also predicted by partial equilibrium models. A marginal increase in the period-t tax in country i lowers resource use in this country and increases resource use in the other country in period t via a decline in p_t. We thus have **intratemporal leakage** between countries, which is imperfect in the sense that unilateral efforts to reduce resource use in a certain period are not completely offset by market reactions in the other country in that period. As in partial equilibrium (where interest rates are exogenous), a fall in p_t is accompanied by a fall in the resource price in the other period to facilitate higher resource use in that period and achieve an equilibrium in the resource market. This **intertemporal leakage** effect impacts all countries alike through changes in world market prices.

A marginal increase in the second-period tax leads to the effect generally known as the **Green Paradox** (Sinclair, 1992; Sinn, 2008), i.e. an expansion of current resource extraction. This result is in line with van der Meijden et al. (2015) and van der Ploeg (2016), who find that, in general equilibrium, an attenuation of the Green Paradox (compared to a partial equilibrium treatment) is the most likely outcome if investment in physical capital is possible. In fact, in their model, a reversal of the Green Paradox, i.e. a reduction in current extraction induced by an increase in future resource taxes, cannot happen, unless the income effect outweighs the substitution effect (which is not supported by findings in the literature and not assumed here).

Denoting the total stock of capital in period t by $k_t = \sum_{l=1}^{2} k^l$, we further derive:

$$\frac{\partial k_1^i}{\partial \tau_1^i} = -\frac{F_{kr}^1}{2\Gamma_1} < 0 \,, \quad \frac{\partial k_1^i}{\partial \tau_2^i} = 0 \,, \tag{15a}$$

$$\frac{\partial k_1^j}{\partial \tau_1^i} = \frac{F_{kr}^1}{2\Gamma_1} > 0 \,, \quad \frac{\partial k_1^j}{\partial \tau_2^i} = 0 \,, \tag{15b}$$

$$\frac{\partial k_1}{\partial \tau_1^i} = 0 \,, \quad \frac{\partial k_1}{\partial \tau_2^i} = 0 \,, \tag{15c}$$

$$\frac{\partial k_2^i}{\partial \tau_1^i} = \frac{(1+\rho_2)\left[F_r^1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}\right]}{2\Delta} \gtreqless 0 \,, \quad \frac{\partial k_2^i}{\partial \tau_2^i} = -\frac{F_{kr}^2 \Delta + \Gamma_2 \left[F_r^1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}\right]}{2\Gamma_2 \Delta} \gtreqless 0 \,, \tag{15d}$$

$$\frac{\partial k_2^j}{\partial \tau_1^i} = \frac{(1+\rho_2)\left[F_r^1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}\right]}{2\Delta} \gtreqless 0 \,, \quad \frac{\partial k_2^j}{\partial \tau_2^i} = \frac{F_{kr}^2 \Delta - \Gamma_2 \left[F_r^1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}\right]}{2\Gamma_2 \Delta} > 0 \,, \tag{15e}$$

$$\frac{\partial k_2}{\partial \tau_1^i} = \frac{(1+\rho_2)\left[F_r^1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}\right]}{\Delta} \gtreqless 0 \,, \quad \frac{\partial k_2}{\partial \tau_2^i} = -\frac{F_r^1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}}{\Delta} \gtreqless 0 \,. \tag{15f}$$

From the first three sets of equations above, it becomes clear that a marginal increase in resource taxes has only limited influence on capital allocation in the first period. While an increase in τ_1^i is to the detriment of the tax-increasing country, this obviously benefits the other country. An increase in τ_2^i does not have any effect on the capital allocation in period one, since capital demand in that period in all countries is equally affected by changes in world market prices. By contrast, second-period capital is more responsive to changes in resource taxes due to their effects on capital accumulation. For a purely substitutive relationship between capital and resources in production, $F_{kr}^2 = 0$, the change in capital use in period two would solely be driven by the change in savings due to the intertemporal reallocation of resource use. We have seen that a marginal increase in τ_t^i lowers domestic and aggregate resource use in period t but increases resource use in the other period. If, for example, it *increases* first-period resource use, more output will be produced and the associated increase in profits will translate one-to-one into higher savings and thus higher capital investment in the second period. With complementarity, $F_{kr}^2 > 0$, capital use is also affected by the change in resource use. To stick with our example, declining second-period resource use would go hand-in-hand with decreasing capital demand (in the tax-increasing country and in aggregate) and an interest rate ρ_2 that is decreasing more significantly than under perfect substitutability, implying lower savings. This effect thus counteracts the first (direct) effect and implies increased savings. It is unclear which effect dominates.

4.2. Capital taxes

A marginal increase in capital taxes κ_1^i (left-hand side) and κ_2^i (right-hand side) has the following effects on world market prices:

$$\frac{\partial \rho_1}{\partial \kappa_1^i} = -\frac{1}{2} < 0 , \quad \frac{\partial \rho_1}{\partial \kappa_2^i} = \frac{F_{kr}^1 (p_1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2})}{2\Delta} \gtreqless 0 , \tag{16a}$$

$$\frac{\partial \rho_2}{\partial \kappa_1^i} = 0 , \quad \frac{\partial \rho_2}{\partial \kappa_2^i} = \frac{F_r^1 F_{kr}^2 - \Omega}{2\Delta} < 0 , \tag{16b}$$

$$\frac{\partial p_1}{\partial \kappa_1^i} = 0 , \quad \frac{\partial p_1}{\partial \kappa_2^i} = \frac{F_{rr}^1 (p_1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2})}{2\Delta} \gtreqless 0 , \tag{16c}$$

$$\frac{\partial p_2}{\partial \kappa_1^i} = 0 , \quad \frac{\partial p_2}{\partial \kappa_2^i} = \frac{p_1 (F_r^1 F_{kr}^2 - F_{rr}^2) - (1+\rho_2) F_{rr}^1 F_{kr}^2 \frac{\partial s}{\partial \rho_2}}{2\Delta} < 0 . \tag{16d}$$

As intuition suggests, a marginal increase in κ_t^i decreases the interest rate in period t, by lowering the demand for capital in that period. A marginal change in κ_1^i does not have any (net) effect on market prices other than that. If we marginally increase κ_2^i, the second-period price for the resource falls, mostly because the assumed complementarity shifts aggregate resource demand downwards. The effects of a change in κ_2^i on first-period prices are ambiguous, depending on the sign of the term $p_1 - F_{kr}^2 \partial s / \partial \rho_2$, which will be explored below.

Concerning changes in investment, we find:

$$\frac{\partial k_1^i}{\partial \kappa_1^i} = \frac{F_{rr}^1}{2\Gamma_2} < 0 , \quad \frac{\partial k_1^i}{\partial \kappa_2^i} = 0 , \tag{17a}$$

$$\frac{\partial k_1^j}{\partial \kappa_1^i} = -\frac{F_{rr}^1}{2\Gamma_2} > 0 , \quad \frac{\partial k_1^j}{\partial \kappa_2^i} = 0 , \tag{17b}$$

$$\frac{\partial k_1}{\partial \kappa_1^i} = 0 , \quad \frac{\partial k_1}{\partial \kappa_2^i} = 0 , \tag{17c}$$

$$\frac{\partial k_2^i}{\partial \kappa_1^i} = 0 , \quad \frac{\partial k_2^i}{\partial \kappa_2^i} = \frac{F_{rr}^2 \Delta + \Gamma_2 (F_r^1 p_1 - \Omega \frac{\partial s}{\partial \rho_2})}{2\Gamma_2 \Delta} < 0 , \tag{17d}$$

$$\frac{\partial k_2^j}{\partial \kappa_1^i} = 0 , \quad \frac{\partial k_2^j}{\partial \kappa_2^i} = -\frac{F_{rr}^2 \Delta - \Gamma_2 (F_r^1 p_1 - \Omega \frac{\partial s}{\partial \rho_2})}{2\Gamma_2 \Delta} > 0 , \tag{17e}$$

$$\frac{\partial k_2}{\partial \kappa_1^i} = 0 , \quad \frac{\partial k_2}{\partial \kappa_2^i} = \frac{F_r^1 p_1 - \Omega \frac{\partial s}{\partial \rho_2}}{\Delta} < 0 . \tag{17f}$$

A marginal increase in κ_1^i leads to a reallocation of capital from the tax-increasing to the other country. However, it has no effects on the accumulation and allocation of capital in period two. The intuition for this is as follows. First, a lower first-period interest rate lowers the capital income of households and the capital costs of firms in both countries. However, due to symmetry, these changes exactly offset one another in each country, with the result that no additional income is generated that can be saved for the future. Second, as we shall see below, lower resource use in the tax-increasing country in period one due to the increase in κ_1^i (and due to complementarity $F_{kr}^1 > 0$) leads to lower savings in that country, but this is exactly offset by higher resource use and thus higher savings in the other country, since aggregate resource use in period one is unaffected. As aggregate capital supply in period two thus remains unaffected, ρ_2 does not change.

For the capital allocation in period two only period-two policies play a role, since demand in either country in that period is unaffected by period-one policies. Similarly, a marginal increase in κ_2^i bears no effect on capital allocation in period one. However, it lowers investment in the tax-increasing country in period two and increases investment in the other country due to the declining prices ρ_2 and p_2. Taken together, aggregate investment in period two falls.

Finally, we have:

$$\frac{\partial r_1^i}{\partial \kappa_1^i} = -\frac{F_{kr}^1}{2\Gamma_2} < 0 , \quad \frac{\partial r_1^i}{\partial \kappa_2^i} = \frac{p_1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}}{2\Delta} \gtreqless 0 , \tag{18a}$$

$$\frac{\partial r_1^j}{\partial \kappa_1^i} = \frac{F_{kr}^1}{2\Gamma_2} > 0 , \quad \frac{\partial r_1^j}{\partial \kappa_2^i} = \frac{p_1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}}{2\Delta} \gtreqless 0 , \tag{18b}$$

$$\frac{\partial r_1}{\partial \kappa_1^i} = 0\,, \quad \frac{\partial r_1}{\partial \kappa_2^i} = \frac{p_1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}}{\Delta} \gtreqless 0\,, \tag{18c}$$

$$\frac{\partial r_2^i}{\partial \kappa_1^i} = 0\,, \quad \frac{\partial r_2^i}{\partial \kappa_2^i} = -\frac{F_{kr}^2 \Delta + \Gamma_2 \left(p_1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}\right)}{2\Gamma_2 \Delta} \gtreqless 0\,, \tag{18d}$$

$$\frac{\partial r_2^j}{\partial \kappa_1^i} = 0\,, \quad \frac{\partial r_2^j}{\partial \kappa_2^i} = \frac{F_{kr}^2 \Delta - \Gamma_2 \left(p_1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}\right)}{2\Gamma_2 \Delta} > 0\,, \tag{18e}$$

$$\frac{\partial r_2}{\partial \kappa_1^i} = 0\,, \quad \frac{\partial r_2}{\partial \kappa_2^i} = -\frac{p_1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}}{\Delta} \gtreqless 0\,. \tag{18f}$$

It is little surprising that resource allocation in period two does not depend on marginal changes in κ_1^i. It is less clear though why aggregate resource extraction is unaffected. The intuition is that the reallocation of capital in period one shifts the resource demand schedules in that period due to complementarity. However, this shift occurs in opposite directions, and, because of symmetry, by the same amount in both countries (which implies that there is no effect on p_1 for a given aggregate extraction in period one). The aggregate resource demand schedule is thus unaffected in period one, and as there is also no effect of a change in κ_1^i on the aggregate demand schedule in period two (discounted by $1 + \rho_2$), aggregate resource extraction does not change. Overall, the fact that increases in κ_1^i have no effect on aggregate resource extraction and capital accumulation is due to the exogenous capital supply in period one and the symmetry assumption. This mechanism underlies the main finding of this paper.

Regarding the effects of a marginal increase in κ_2^i, the signs of most of the equations above depend on the sign of the term $p_1 - F_{kr}^2 \partial s/\partial \rho_2$. Assume for the moment a purely substitutive technology, i.e. $F_{kr}^2 = 0$. In this case, all effects have a unique sign. As capital becomes more expensive for the production firm in country *i* in period two due to the marginal capital tax increase, it will substitute away from capital and demand more resources. The accompanying drop in the second-period interest rate also causes the resource price to grow less over time, i.e. p_2 falls, as well, by $p_1 d\rho_2$. In turn, this drop in p_2 stimulates resource use in the other country in the same period. As a result, total resource use in period two goes up and first-period resource use (and thus pollution) goes down. A unilateral increase in second-period capital taxes thus *slows down* resource extraction whenever capital and resources are perfect substitutes.

For $F_{kr}^2 > 0$, there is a second effect that arises from the decline in ρ_2 due to the increase in κ_2^i. With a lower ρ_2, less savings will be carried over from period one to period two. Consequently, less capital can be used in production in all countries in period two, which, by complementarity, also reduces aggregate resource use in that period. If this effect is sufficiently strong, which is the case either for a sufficiently high degree of complementarity or a sufficiently strong capital-supply reaction, as measured by $\partial s/\partial \rho_2$, a unilateral increase in second-period capital taxes *speeds up* resource extraction. Overall, the sign of $p_1 - F_{kr}^2 \partial s/\partial \rho_2$ is determined by the complex interplay of these terms in general equilibrium and is difficult to qualify analytically since the degree of complementarity between capital and resources, as measured by F_{kr}^2, also plays a role in determining p_1.

Summing up the comparative statics results, we can make the following proposition.

Proposition 1 (Effects of unilateral tax policies). *Unilateral marginal increases in*

1. *the period-t resource tax shift resource use to the other country and decrease resource use in period $t = 1,2$ in aggregate. This is equivalent to less than 100% intratemporal leakage due to the tax increase and implies Green Paradox effects. Furthermore, the effects on capital accumulation are ambiguous.*
2. *the period-one capital tax has a detrimental effect on the allocation of capital and resources in period one from the point of view of the government increasing taxes, and no effect on capital accumulation and the rate of resource extraction.*
3. *the period-two capital tax has a detrimental effect on investment and an ambiguous effect on resource use in period two in the tax-increasing country. They lead to a decrease in aggregate first-period extraction if and only if $p_1 - F_{kr}^2 \partial s/\partial \rho_2 > 0$, and to an increase in extraction if and only if $p_1 - F_{kr}^2 \partial s/\partial \rho_2 < 0$.*

Marginal changes in the period-one capital tax are thus neutral with respect to the intertemporal allocation of resources, while changes in the period-two capital tax have ambiguous effects. Furthermore, unilaterally lowering the first-period capital tax leads to an inflow of both capital and resources. These effects are important to keep in mind for the analysis of strategic tax-setting by governments, which will be discussed in the next section.

5. Pareto-optimal policies and strategic interactions

In this section, I derive the benchmark case of Pareto-optimal policies and characterize the Nash equilibrium tax rates under different tax regimes.

5.1. Pareto-optimal policies

Pareto-optimal policies are found by maximizing lifetime utility W^i, equation (7), subject to $W^j = \overline{W^j}, j \neq i$, by choosing κ_1^i, τ_1^i, κ_2^i and τ_2^i. Further constraints are the budget constraints of each household, given by (6), where firm profits and lump-sum transfers (both of which are exogenous from the perspective of households) are replaced by (1), (3) and (5). Furthermore, the conditions of utility maximization, (8)–(9), profit maximization, (2) and (4), and the market reactions as described by (13a)–(18f) need to be considered. Focusing on the symmetric solution with $\overline{k^i} = k_1^i$, $s^i = k_2^i = s$ and $q_t^i = r_t^i$ for all $i = 1, 2$ and for all $t = 1, 2$, the first-order conditions for the tax rates in country i read[16]:

$$(1+\rho_2)\left[\tau_1^i \frac{\partial r_1}{\partial \tau_1^i} + \kappa_1^i \frac{\partial k_1}{\partial \tau_1^i}\right] + \tau_2^i \frac{\partial r_2}{\partial \tau_1^i} + \kappa_2^i \frac{\partial k_2}{\partial \tau_1^i} - \frac{2D'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \tau_1^i} = 0 \ , \tag{19}$$

$$(1+\rho_2)\left[\tau_1^i \frac{\partial r_1}{\partial \tau_2^i} + \kappa_1^i \frac{\partial k_1}{\partial \tau_2^i}\right] + \tau_2^i \frac{\partial r_2}{\partial \tau_2^i} + \kappa_2^i \frac{\partial k_2}{\partial \tau_2^i} - \frac{2D'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \tau_2^i} = 0 \ , \tag{20}$$

$$(1+\rho_2)\left[\tau_1^i \frac{\partial r_1}{\partial \kappa_1^i} + \kappa_1^i \frac{\partial k_1}{\partial \kappa_1^i}\right] + \tau_2^i \frac{\partial r_2}{\partial \kappa_1^i} + \kappa_2^i \frac{\partial k_2}{\partial \kappa_1^i} - \frac{2D'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \kappa_1^i} = 0 \ , \tag{21}$$

$$(1+\rho_2)\left[\tau_1^i \frac{\partial r_1}{\partial \kappa_2^i} + \kappa_1^i \frac{\partial k_1}{\partial \kappa_2^i}\right] + \tau_2^i \frac{\partial r_2}{\partial \kappa_2^i} + \kappa_2^i \frac{\partial k_2}{\partial \kappa_2^i} - \frac{2D'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \kappa_2^i} = 0 \ . \tag{22}$$

Terms that are zero as per the comparative statics above are shaded in grey.

Rearranging these conditions and denoting $\kappa_1^i = \kappa_1^*$, $\kappa_2^i = \kappa_2^*$, $\tau_1^i = \tau_1^*$ and $\tau_2^i = \tau_2^*$ for all $i = 1, 2$ yields[17]:

$$\kappa_1^* = \kappa_2^* = 0 \ , \qquad \tau_1^* - \frac{\tau_2^*}{1+\rho_2} = \frac{2D'(r_1)}{U'(c_1^i)} = \frac{2D'(r_1)}{\epsilon(1+\rho_2)} \ . \tag{23}$$

The Pareto-optimal capital tax rates κ_1^* and κ_2^* equal zero. The social marginal environmental damage, $2D'(r_1)$, from aggregate resource use in the first period, expressed in units of the first-period consumption good, is fully internalized through the use of resource taxes. There is one degree of freedom in setting Pareto-optimal resource taxes τ_1^* and τ_2^*. Either one of the two tax rates is set equal to zero together with a positive first-period/negative second-period resource tax or, alternatively, a convex combination of both instruments that satisfies the second equation in (23) is implemented. In either case, the resource tax profile falls over time, with a weakly positive tax in the first and a weakly negative tax in the second period.[18] The intuition is that it is not the static value of the tax rate in one of the periods that matters for the internalization of the external effect, but rather its development over time. Only a decreasing tax schedule incentivizes production firms to demand less resources today and more resources tomorrow compared to a laissez-faire scenario without taxes.

5.2. Decentralized equilibrium

I now proceed to characterize the equilibrium of the Nash game, assuming that governments can fully commit to the vector of tax rates in the first period, which implies that they do not deviate from their announced policies in the second period.[19]

In each country i, the benevolent government maximizes its resident's lifetime utility by choosing κ_1^i, τ_1^i, κ_2^i and τ_2^i, taking the policies of the other country as given. In doing so, it takes the household's budget constraint into account, equation (6), and replaces firm profits by (1) and (3) and lump-sum transfers by (5) in these equations. It also considers the conditions of utility maximization, (8)–(9), profit maximization, (2) and (4), and the market reactions, (13a)–(13d), (14a), (14d), (15a), (15d), (16a)–(16d), (17a), (17d), (18a) and (18d). Assuming that a symmetric equilibrium with an interior solution exists, it is described by the following first-order conditions:

$$(1+\rho_2)\left[\tau_1^i \frac{\partial r_1^i}{\partial \tau_1^i} + \kappa_1^i \frac{\partial k_1^i}{\partial \tau_1^i}\right] + \tau_2^i \frac{\partial r_2^i}{\partial \tau_1^i} + \kappa_2^i \frac{\partial k_2^i}{\partial \tau_1^i} - \frac{D'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \tau_1^i} = 0 \ , \tag{24}$$

[16] The resource quantities supplied by each country are, in principle, indeterminate, as argued in Section 3.2 and footnote 14 (only in symmetric equilibrium, we have $q_t^i = r_t^i$ and thus $s^i = k_2^i$ for all i). This also implies that the derivatives of the supplied quantities with respect to the tax rates $\square = \kappa_1^i, \tau_1^i, \kappa_2^i, \tau_2^i$ are zero for all $t = 1, 2$: $\partial q_t^i / \partial \square = 0$.

[17] An interesting case arises for $\epsilon = 0$. While the economy is still well defined in this case, households do not save anything for the second period. As a result, the markets in the second period break down. Deriving all comparative statics when only markets in the first period exist, and plugging those into equations (19)–(22) reveals that any combination of capital and resource taxes is efficient. Therefore, even the Nash equilibrium tax rates are efficient. This generalizes the efficiency result obtained by Ogawa and Wildasin (2009) for the case where capital and resources are separate inputs to production.

[18] Pareto-optimal resource tax rates that decline over time have also been found by, e.g. Sinclair (1992, 1994) and Golosov et al. (2014). van der Ploeg (2016) derives basically the same equation as the second equation in (23) for the case where oil is fully exhausted by the end of period two.

[19] Obviously, commitment is not an innocuous assumption but employed even in many one-country models in which capital taxation is used as an instrument, see, e.g., Barrage (2015). The problem of time(in)consistency is addressed in the discussion section.

$$(1+\rho_2)\left[\tau_1^i\frac{\partial r_1^i}{\partial \tau_2^i}+\kappa_1^i\frac{\partial k_1^i}{\partial \tau_2^i}\right]+\tau_2^i\frac{\partial r_2^i}{\partial \tau_2^i}+\kappa_2^i\frac{\partial k_2^i}{\partial \tau_2^i}-\frac{D'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \tau_2^i}=0\ , \tag{25}$$

$$(1+\rho_2)\left[\tau_1^i\frac{\partial r_1^i}{\partial \kappa_1^i}+\kappa_1^i\frac{\partial k_1^i}{\partial \kappa_1^i}\right]+\tau_2^i\frac{\partial r_2^i}{\partial \kappa_1^i}+\kappa_2^i\frac{\partial k_2^i}{\partial \kappa_1^i}-\frac{D'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \kappa_1^i}=0\ , \tag{26}$$

$$(1+\rho_2)\left[\tau_1^i\frac{\partial r_1^i}{\partial \kappa_2^i}+\kappa_1^i\frac{\partial k_1^i}{\partial \kappa_2^i}\right]+\tau_2^i\frac{\partial r_2^i}{\partial \kappa_2^i}+\kappa_2^i\frac{\partial k_2^i}{\partial \kappa_2^i}-\frac{D'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \kappa_2^i}=0\ . \tag{27}$$

Each government trades off the marginal benefits with the marginal costs of tax changes. These changes affect tax revenues by altering the domestic tax bases in both periods (first four terms in the equations above), except for $\partial k_2^i/\partial \tau_2^i=\partial k_2^i/\partial \kappa_1^i=\partial k_1^i/\partial \kappa_2^i=\partial r_2^i/\partial \kappa_1^i=0$, and environmental damage by altering aggregate resource use in the first period (last term), except for $\partial r_1/\partial \kappa_1^i=0$. Compared to Pareto-optimal policies as characterized by equations (19)–(22), we observe that governments do not take into account *aggregate* pollution damages and the effects of their policies on *aggregate* tax revenues.

To gain an understanding of governments' strategic behavior and the welfare effects of different tax portfolios, I will first discuss the Nash equilibrium with resource taxes only, then the equilibrium with period-one instruments, and, finally, the equilibrium in which all instruments are at the governments' disposal.[20]

5.2.1. Nash equilibrium with resource taxes only

Because of their partial equilibrium nature, most models in the literature only allow governments to have resource taxes at their disposal. In this case, equations (26) and (27) no longer apply, and the optimal tax rates in the symmetric Nash equilibrium in country i can be obtained by rearranging conditions (24) and (25) for $\kappa_1^i=\kappa_2^i=0$ to yield:

$$\tau_1^i=\frac{-2D'(r_1)F_{kk}^2\Gamma_1\Theta}{\epsilon[F_{kk}^1F_{kk}^2\Delta-\Theta(F_{kk}^1\Gamma_2+F_{kk}^2\Gamma_1)]}>0\ ,\quad \tau_2^i=\frac{2D'(r_1)F_{kk}^1\Gamma_2\Theta}{\epsilon[F_{kk}^1F_{kk}^2\Delta-\Theta(F_{kk}^1\Gamma_2+F_{kk}^2\Gamma_1)]}<0\ . \tag{28}$$

While the taxes' time profile in the Nash equilibrium falls, as in the efficient solution, the degree of freedom in setting this tax-subsidy combination vanishes. Now a strictly positive tax in the first and a strictly negative tax rate in the second period prevail. According to equations (24) and (25), the benefit of a marginal increase in τ_1^i or marginal decrease in τ_2^i is that domestic and aggregate resource use in the first period are curbed, which reduces environmental damage. The associated marginal costs are the loss of resource tax revenue in the first period and an increase in the subsidy on resource use in the second period.

For a better understanding of the effects at work, we examine the policy externalities, i.e. the effects of marginal tax increases in country i on welfare in country $j\neq i$. Starting from a symmetric equilibrium, we obtain the following for $\square=\tau_1,\tau_2$:

$$\frac{\partial W^j}{\partial \square^i}=-D'(r_1)\frac{\partial r_1}{\partial \square^i}+\epsilon(1+\rho_2)\tau_1^j\frac{\partial r_1^j}{\partial \square^i}+\epsilon\tau_2^j\frac{\partial r_2^j}{\partial \square^i}\ . \tag{29}$$

The first term illustrates the environmental externality imposed on country j, while the two other terms are private income externalities that change the tax bases in country j due to the mobility of resources.[21] Inserting the Nash equilibrium tax rates and the comparative statics results into (29) leads to the following proposition.

Proposition 2 (Efficiency characteristics of resource taxes). *A marginal increase in the resource tax τ_1^i or a marginal decrease in τ_2^i exerts a positive environmental externality and private income externalities that have different signs but are strictly positive in aggregate, on country j.*

Both types of externalities thus go in the same direction. With only one instrument at the governments' disposal, we could assess the efficiency properties of the Nash equilibrium using these policy externalities. A positive externality would then imply that the tax rate in the Nash equilibrium is set inefficiently low, and vice versa, since a marginal increase in the tax rate in country i would increase welfare in country $j\neq i$, while this would have no impact on welfare in country i (as per the first-order condition). Due to the complex interplay of tax rates in the multi-policy case, this argument does not hold here. Furthermore, we cannot simply compare the Pareto-optimal tax-subsidy combination with the tax-subsidy combination in the Nash equilibrium because world market prices and the derivatives contained in the tax rate equations are endogenous and thus different.

[20] In the numerical illustration in Section 5.3, the Nash equilibrium will also be examined for other cases, e.g., in the absence of factor mobility, and under tax regimes in which different subsets of instruments are available to governments.

[21] As tax revenues are recycled in a lump-sum fashion to consumers, I refer to these externalities as 'private income' externalities like in Eichner and Runkel (2012). Introducing a physical public good into this model would not change any of the results derived here except that the 'private income' externalities could then be called 'fiscal'.

5.2.2. Nash equilibrium with period-one taxes

To examine a case in which governments cannot commit to future taxation and can only carry out period-one policies, the first-order conditions (25) and (27) drop out, and (24) and (26) yield:

$$\tau_1^i = \frac{2D'(r_1)F_{rr}^1\Theta}{\epsilon\left[(1+\rho_2)F_{rr}^1F_{kk}^2\frac{\partial s}{\partial\rho_2}-\Delta\right]} > 0\ , \quad \kappa_1^i = \frac{2D'(r_1)F_{kr}^1\Theta}{\epsilon\left[(1+\rho_2)F_{rr}^1F_{kk}^2\frac{\partial s}{\partial\rho_2}-\Delta\right]} < 0\ . \tag{30}$$

As before, resource use in period one is taxed at a strictly positive rate. At the same time, capital investment is now subsidized, as long as there is some complementarity between capital and resources in production, as measured by $F_{kr}^1 > 0$. If capital and resources were perfect substitutes, i.e. $F_{kr}^1 = 0$, no subsidy or tax would be levied on capital in the Nash equilibrium.

According to equation (24), the benefit of a marginal increase in τ_1^i now consists not only in the reduction in pollution but also in the reduction of subsidy payments on capital, whereas the associated cost is the loss of first-period resource tax revenue. Similarly, equation (26) informs us that a marginal increase in κ_1^i does not have any impact on environmental damage, because aggregate first-period resource use remains the same (see equation (18c)). Therefore, the sign of the capital tax is determined by the term in square brackets in equation (26). As the derivatives in this bracket are both negative and τ_1^i must be positive due to its effect on pollution, the capital tax is set at a strictly negative rate. In other words, the capital tax rate is set such that the marginal loss in resource tax revenue is exactly offset by the marginal income gain due to lower subsidy payments on capital. Therefore, a marginal increase in τ_1^i has higher benefits when the government can implement a period-one capital tax, as compared to the case when only the first-period resource tax is available (a case that will be illustrated in Section 5.3). The subsidization of capital thus facilitates a higher resource tax in period one.

Again, we examine the policy externalities. For $\square = \tau_1, \kappa_1$, we obtain:

$$\frac{\partial W^j}{\partial\square^i} = -D'(r_1)\frac{\partial r_1}{\partial\square^i} + \epsilon(1+\rho_2)\left[\tau_1^j\frac{\partial r_1^j}{\partial\square^i} + \kappa_1^j\frac{\partial k_1^j}{\partial\square^i}\right]\ . \tag{31}$$

As in the regime with resource taxes only, we observe both environmental and private income externalities. If the Nash equilibrium tax rates and the comparative statics results are inserted into the above equation, I can show that the following proposition holds true.

Proposition 3 (Efficiency characteristics of period-one policies). *A marginal increase in τ_1^i exerts both a positive environmental externality and a positive aggregate private income externality on country j. A marginal increase in κ_1^i does not impose any net externalities on the other country.*

In contrast to the resource tax, the capital tax is non-distortionary, since the environmental externality is zero and the two private income externalities cancel each other out. This suggests that the capital subsidy can be used to correct for the feared outflow of capital and resources induced by the positive resource tax. As we shall see in the numerical illustration in Section 5.3, granting a subsidy to capital in addition to the resource tax facilitates a higher resource tax and leads to an increase in domestic and global equilibrium welfare.

5.2.3. Nash equilibrium with period-one and period-two taxes

If each government is equipped with the full set of tax instruments, the first-order conditions (24)–(27) can be rearranged to yield the following equilibrium tax rates:

$$\tau_1^i = D'(r_1)\frac{F_{rr}^1\left[1-2F_{kk}^2\frac{\partial s}{\partial\rho_2}\right]}{\epsilon(\Delta+\Lambda)} > 0\ , \quad \kappa_1^i = D'(r_1)\frac{F_{kr}^1\left[1-2F_{kk}^2\frac{\partial s}{\partial\rho_2}\right]}{\epsilon(\Delta+\Lambda)} < 0\ , \tag{32}$$

$$\tau_2^i = -D'(r_1)\frac{F_{rr}^2-2\Gamma_2\frac{\partial s}{\partial\rho_2}-p_1F_{kr}^2}{\epsilon(\Delta+\Lambda)} < 0\ , \quad \kappa_2^i = D'(r_1)\frac{F_{kk}^2p_1-F_{kr}^2}{\epsilon(\Delta+\Lambda)} > 0\ . \tag{33}$$

As before, resource taxes decline over time, with a strictly positive tax in the first period and a strictly negative tax in the second. Interestingly, the time path of the capital tax is exactly the opposite, with a strictly *negative* tax in period one (as before) and a strictly *positive* tax in period two. It is not particularly surprising that the capital tax in the first period is negative. We have seen that a marginal decrease in this tax leads to an inflow of both resources and capital in the first period, while it has no effect on intertemporal resource allocation and capital accumulation. If capital and resources were perfect substitutes, i.e. $F_{kr}^1 = 0$, then κ_1^i would again be zero.

The sign of the second-period capital tax is more surprising, because most comparative statics results with respect to κ_2^i were ambiguous in sign and because κ_2^i is strictly positive even when capital and resources are perfect substitutes in period two. This indicates that the capital tax in the second period is distinctly different from the capital tax in period one. By inspecting the terms in the numerator of κ_2^i, we can shed some light on the effects at work, keeping in mind that the aim of country i is to increase aggregate resource use in period two. This implies costs due to the subsidization of domestic resource use in period two. By unilaterally increasing the capital tax from zero to a positive value the government can make sure that no exceedingly

high subsidy has to be paid on resource use. The reason is that, due to complementarity, part of the subsidy payments can be avoided because the capital tax makes domestic resource use less attractive. At the same time, the positive capital tax induces two effects that are beneficial for country *i*. First, the interest rate ρ_2 falls (equation (16b)), which makes investment in the non-tax-increasing country more attractive and thus spurs, due to complementarity, resource demand abroad. Second, due to a Hotelling rule effect, the resource price p_2 falls (equation (16d)), which also induces the production firm in the other country to demand more resources in the second period. The latter effect applies even to the case of a purely substitutive production technology.

For $\square = \kappa_1, \tau_1, \kappa_2, \tau_2$, we get the following policy externalities:

$$\frac{\partial W^j}{\partial \square^i} = -D'(r_1)\frac{\partial r_1}{\partial \square^i} + \epsilon(1+\rho_2)\left[\tau_1^j \frac{\partial r_1^j}{\partial \square^i} + \kappa_1^j \frac{\partial k_1^j}{\partial \square^i}\right] + \epsilon\left[\tau_2^j \frac{\partial r_2^j}{\partial \square^i} + \kappa_2^j \frac{\partial k_2^j}{\partial \square^i}\right] . \tag{34}$$

As in the regime with resource taxes only, it can easily be shown that a marginal increase in τ_1^i or a marginal decrease in τ_2^i exerts a positive externality on country $j \neq i$. As for the externalities associated with capital taxation, we can make the following proposition.

Proposition 4 (Efficiency characteristics of capital taxes). *The capital tax in the first period does not induce any distortions, but the second-period capital tax exerts a positive or negative externality on the other country, depending on the sign of the term* $p_1 - 2F_{kr}^2 \partial s/\partial \rho_2$.

As we have seen in the comparative statics, a unilateral marginal increase in the first-period capital tax does not have an effect on the rate of extraction and capital accumulation. It does not change ρ_2 and thus the relative prices of resources across periods, $p_2/p_1 = 1 + \rho_2$. By contrast, a marginal increase in one country's second-period capital tax does have an effect on the rate of extraction and capital accumulation, since it changes ρ_2 and thus relative prices p_2/p_1. This makes the second-period capital tax distortionary. If the elasticity of substitution between capital and resources is high (or low), as measured by a low (or high) F_{kr}^2, the externality of κ_2^i is positive (or negative).

Before examining the efficiency properties of this tax portfolio relative to other tax portfolios in Section 5.3, I analyze the local efficiency properties of decentralized policy-making under different tax regimes in the following subsection.

5.2.4. Local efficiency properties of decentralized policy-making

All tax portfolios examined above have been shown to have at least some distortionary element (the resource taxes and the second-period capital tax) and therefore most likely do not result in an efficient allocation in the second best. It is of particular interest whether these tax portfolios bring about inefficiently high or inefficiently low aggregate resource use and thus pollution in period one. As mentioned earlier, the existence of more than one instrument makes it impossible to make use of policy externalities to assess the efficiency properties of the Nash equilibrium. However, it *is* possible to analyze whether, starting from the Nash equilibrium allocation, a Pareto improvement can be achieved by marginally decreasing resource use in the two countries in period one by the same amount. To this end, suppose that the government in country *i* can give away a marginal unit of the resource in period one to its domestic production firm for free. This will have an impact on capital and resource demand in all periods and all countries (except, of course, for the resource demand in country *i* in period one) and thus also on world market prices and capital accumulation. Computing the comparative statics for the marginal increase in r_1^i and evaluating the derivative of the welfare of countries *i* and *j* with respect to r_1^i at the Nash equilibrium ('NE') yields for all tax portfolios:

$$\frac{\partial W^i}{\partial r_1^i}|_{NE} = 0 , \quad \frac{\partial W^j}{\partial r_1^i}|_{NE} < 0 , \tag{35}$$

where the equilibrium tax rates for the respective tax portfolio have been inserted. This leads to the following proposition, the proof for which can be found in Appendix A.2.

Proposition 5 (Pareto improvement over Nash equilibrium allocation). *Starting from the Nash equilibrium, a simultaneous marginal decrease in resource use in the two countries brings about a Pareto improvement. This holds for each tax portfolio.*

A marginal change in resource use in country *i* does not have any effect on domestic welfare in the Nash equilibrium, since tax rates have been set such that resource use in the first period is optimal from each government's point of view. However, a decrease in r_1^i benefits the other country.

Whether aggregate resource use in the Nash equilibrium is too high or too low compared to the Pareto optimum cannot be inferred from the above equations, because the tax rates are also changing on the path from the Nash equilibrium to the Pareto optimum, and welfare might thus not monotonically increase along this path.[22]

[22] For all parameter combinations used in the paper, it can be shown numerically that welfare is indeed monotonically increasing on the path from the Nash equilibrium to the Pareto optimum. The relevant Mathematica script can be obtained from the author upon request.

5.3. Numerical illustration

So far, we have seen that in the Nash equilibrium, countries can be made better off if resource use in the first period is lowered. What we cannot infer analytically, however, is whether the rate of resource extraction is inefficiently high, or how the different tax regimes analyzed above compare with respect to the level of welfare they yield in equilibrium. To this end, some numerical illustrations are provided below.[23] I am particularly interested in whether there are any welfare gains to be made from complementing the resource tax portfolio with capital taxes, and which role the elasticity of substitution between capital and resources and the capital supply elasticity play in this regard.

In order to have an additional point of reference, I first sketch the Nash equilibrium under autarky, i.e. when factors of production are immobile in both periods. In this case, there are two purely national capital and resource markets in each period. I denote the prices on these markets by ρ_1^i, ρ_2^i, p_1^i and p_2^i in country i. The modified comparative statics of unilateral marginal tax increases as well as the first-order conditions are derived in Appendix A.3. Government maximization yields the following tax rates in the autarky Nash equilibrium:

$$\kappa_1^i = \kappa_2^i = 0\,, \qquad \tau_1^i - \frac{\tau_2^i}{1+\rho_2^i} = \frac{D'(r_1)}{\epsilon(1+\rho_2^i)}\,. \tag{36}$$

The government thus internalizes the environmental externality imposed on its own utility by choosing a convex combination of resource taxes. This is in fact the standard textbook case in which environmental spillovers are the only externality.[24] As the capital and resource allocation in other countries cannot be influenced via domestic tax policies, there is no role for capital taxation in a world of closed economies.

For the numerical simulations, I choose a logarithmic first-period utility function and (without loss of generality) a linear damage function such that equation (7) now reads:

$$W^i = \ln(c_1^i) - \delta r_1 + \epsilon c_2^i\,, \tag{37}$$

where $\delta > 0$ is a damage parameter. The linear damage specification is in line with the assumptions made in complex integrated assessment and general equilibrium climate-economy models (see, for example, Nordhaus and Boyer, 2000; Golosov et al., 2014), in which climate damage is approximately linear in relation to the greenhouse gas concentration in the atmosphere. The reason for this is that typically, temperature is assumed to increase logarithmically with higher concentrations, whereas damage is assumed to be exponential or polynomial in relation to temperature.

To model production, I use standard constant elasticity of substitution (CES) functions:

$$F^t(k_t^i, r_t^i) = \left[\beta_t (k_t^i)^{\alpha_t} + (1-\beta_t)(r_t^i)^{\alpha_t}\right]^{\frac{z}{\alpha_t}}\,, \tag{38}$$

where z describes the degree of homogeneity and $z < 1$ is assumed because of decreasing returns to scale. Furthermore, β_t is the share parameter for capital in period $t = 1, 2$, $(1-\beta_t)$ the one for resources. The elasticity of substitution $\sigma_t \geq 0$ in period t equals $1/(1-\alpha_t)$, i.e. when α_t is lower, capital and resources are more complementary in that period in production.[25] Note that for F_{kr}^t to be positive, $z > \alpha_t$ has to hold.[26]

As for the parameters, I assume a discount rate of 3% per year as in Nordhaus and Boyer (2000), which implies an ϵ of 0.74 if period one covers 10 years and an ϵ of 0.55 if it covers 20 years. For the simulation, I take an intermediate value of 0.65. As capital is relatively more important than energy in production, I assume a share of $\beta_1 = \beta_2 = 0.8$ for capital. It has been estimated in the literature that capital and energy are either complements or weak substitutes. In a recent survey of the literature by Costantini and Paglialunga (2014), σ_t was found to be roughly in the range between 0.1 and 1.6, depending on, among other things, the specification of the production function. This implies values for α_t between −9 and +0.4. The elasticity of substitution and the damage parameter δ are chosen such that the loss of welfare due to climate change is 10% or higher in a laissez-faire scenario compared to the first-best, which is in line with Hsiang et al. (2017), who project that an increase in temperature of 4–8 °C would imply GDP losses in the range of 1.5–15.7% for the US. This implies $\delta = 0.35$. Furthermore, the initial resource and capital endowments are normalized to unity ($Q^i = \overline{k^i} = 1$), and $z = 0.95$.

Table 1 illustrates the results obtained under different scenarios for varied elasticities of substitution ($\sigma_t = 1/3$ vs. $\sigma_t = 2/3$). The laissez-faire scenario involves no government intervention (all tax rates equal zero). 'NE ($\kappa_1^i, \tau_1^i, \kappa_2^i, \tau_2^i$)' stands for the Nash equilibrium in which only the tax rates indicated in parentheses are active, i.e. at the governments' disposal. In particular, I examine the NE under autarky and the ones with either only a resource tax in period one, resource taxes in both periods, only period-one taxes, resource taxes in both periods plus a first-period or a second-period capital tax or all instruments at the governments' disposal.[27] In the columns, the variables of interest are depicted, with the market prices in parentheses below the

[23] The Mathematica scripts can be obtained from the author upon request.

[24] To see this, cf. equation (29) where the private income externalities are zero under autarky since it holds for all $t = 1, 2$ and $j \neq i$: $\partial r_t^j / \partial \tau_1^i = \partial r_t^j / \partial \tau_2^i = 0$.

[25] σ_1 and σ_2 could be the same or different. In the latter case, one would assume that capital and resources are less complementary in period two compared to period one due to resource-saving technological progress.

[26] Strict quasi-concavity requires $\alpha_t < 1$ (Uzawa, 1962), which holds, since I assume decreasing returns to scale and positive cross-partial derivatives F_{kr}^t. Thus, $\alpha_t < z < 1$.

[27] The equilibrium tax rates for portfolios not analyzed in the main text can be found in Appendix A.4.

Table 1
Simulation results for $z = 0.95$, $Q^i = \overline{k^i} = 1$, $\beta_1 = \beta_2 = 0.8$, $\delta = 0.35$, $\epsilon = 0.65$. (Note that the tax rates under the different regimes are not the same.)

	$\alpha_1 = \alpha_2 = -2\ (\sigma_1 = \sigma_2 = 1/3)$						
	r_1^i ($p_1^{(i)}$)	r_2^i ($p_2^{(i)}$)	k_1^i ($\rho_1^{(i)}$)	k_2^i ($\rho_2^{(i)}$)	τ_1^i κ_1^i	τ_2^i κ_2^i	$D(r_1)$ W^i/W^*
Laissez-faire	.6117	.3883	1	.7669	0	0	.4282
	(.5424)	(.7552)	(.4965)	(.3923)	0	0	.8990
Pareto optimum	.4357	.5643	1	.7835	.6737	0	.305
	(.2506)	(.4006)	(.3059)	(.5985)	0	0	1
NE autarky	.5167	.4833	1	.7889	.3582	0	.3617
	(.3641)	(.5473)	(.3985)	(.5034)	0	0	.9772
NE $(0, \tau_1^i, 0, 0)$	.606	.394	1	.769	.0216	0	.4242
	(.5301)	(.7415)	(.4911)	(.3989)	0	0	.9051
NE $(0, \tau_1^i, 0, \tau_2^i)$	.5995	.4005	1	.7714	.0213	-.0352	.4196
	(.5412)	(.7612)	(.4847)	(.4065)	0	0	.9118
NE $(\kappa_1^i, \tau_1^i, 0, 0)$	.5279	.4721	1	.7879	.3159	0	.3695
	(.3822)	(.5696)	(.5723)	(.4903)	-.1616	0	.9709
NE $(\kappa_1^i, \tau_1^i, 0, \tau_2^i)$	.4964	.5036	1	.7897	.4204	-.0231	.3475
	(.3479)	(.5313)	(.5777)	(.5271)	-.2018	0	.9871
NE $(0, \tau_1^i, \kappa_2^i, \tau_2^i)$	.5702	.4298	1	.7182	.0202	-.2351	.3991
	(.5939)	(.8087)	(.4554)	(.3617)	0	.13	.9353
NE $(\kappa_1^i, \tau_1^i, \kappa_2^i, \tau_2^i)$	.5279	.4721	1	.7505	.2368	-.1406	.3695
	(.4612)	(.6633)	(.5319)	(.4382)	-.1211	.0821	.9691
	$\alpha_1 = \alpha_2 = -1/2\ (\sigma_1 = \sigma_2 = 2/3)$						
Laissez-faire	.6172	.3828	1	.9201	0	0	.432
	(.3359)	(.5252)	(.6515)	(.5638)	0	0	.8329
Pareto optimum	.2923	.7077	1	.8503	.6243	0	.2046
	(.1384)	(.2387)	(.4821)	(.725)	0	0	1
NE autarky	.4209	.5791	1	.8985	.3234	0	.2946
	(.193)	(.3213)	(.5641)	(.6649)	0	0	.9681
NE $(0, \tau_1^i, 0, 0)$	.5912	.4088	1	.9205	.0432	0	.4139
	(.3097)	(.4889)	(.6417)	(.5787)	0	0	.8558
NE $(0, \tau_1^i, 0, \tau_2^i)$	.5636	.4364	1	.9198	.0453	-.0674	.3945
	(.3273)	(.5217)	(.6307)	(.5939)	0	0	.8785
NE $(\kappa_1^i, \tau_1^i, 0, 0)$	.3709	.6291	1	.8836	.4228	0	.2597
	(.1697)	(.2864)	(.685)	(.6882)	-.1496	0	.9873
NE $(\kappa_1^i, \tau_1^i, 0, \tau_2^i)$	.3226	.6774	1	.8648	.5274	-.018	.2258
	(.1603)	(.2743)	(.6661)	(.7107)	-.1621	0	.9979
NE $(0, \tau_1^i, \kappa_2^i, \tau_2^i)$	.4985	.5015	1	.8481	.0459	-.2258	.349
	(.3821)	(.5815)	(.6027)	(.5218)	0	.1252	.9218
NE $(\kappa_1^i, \tau_1^i, \kappa_2^i, \tau_2^i)$	.4266	.5734	1	.8672	.2475	-.1073	.2986
	(.2614)	(.4197)	(.6679)	(.6055)	-.1008	.0664	.9646

associated choice variables of the firms. $p_t^{(i)}$ and $\rho_t^{(i)}$ denote the equilibrium prices in national and international factor markets in period t (the former is denoted by superscript $^{(i)}$, the latter without). In the last column, environmental damage $D(r_1)$ and welfare levels W^i relative to the first-best welfare level W^* are displayed. The chosen parameter combinations are just exemplary and the derived findings hold qualitatively for all other permutations.[28]

Obviously, laissez-faire and Pareto optimum describe the two extreme cases, for which resource extraction and welfare are highest/lowest. For example, in the upper panel of Table 1, 61.17% of all resources are extracted in period one in the absence of any policies, while Pareto-efficient policies would imply that only 43.57% are extracted. As a result, the welfare loss under laissez-faire is slightly higher than 10% compared to the first-best. Unsurprisingly, we find that the Nash equilibrium in either regime entails lower welfare than in the first-best, which is implied by higher resource extraction in period one.

Numerical Finding 1 (Inefficiently high rate of resource extraction)

In the Nash equilibrium under either tax regime, resource use in the first period and thus emissions are inefficiently high. This holds irrespective of whether production factors are mobile or not.

This finding generalizes the results obtained by Eichner and Runkel (2012) to tax portfolios with more than one tax. For the case of perfect pollution spillovers ($\beta = 1$ in their model), Eichner and Runkel find an inefficiently low tax rate on capital and thus emissions, implying inefficiently high pollution.[29] While their analysis is limited to competition over capital taxes, which are equivalent in their model to taxes on emissions because of the assumption of proportionality between capital and emissions,

[28] For some parameter combinations though, the solution algorithm did not converge for all tax regimes.

[29] This is indeed the standard result in the environmental tax competition literature. Only Oates and Schwab (1988) and Ogawa and Wildasin (2009) find decentralized policy-making to be efficient, while it has been shown that there is a race to the top in environmental regulations when pollution affects the marginal productivity of capital (Rauscher, 1997a, 1997b) or when households anticipate government policies (Withagen and Halsema, 2013).

this paper explicitly accounts for the fact that emissions are not simply a by-product of investment but caused by the burning of fossil resources in production and can be substituted for capital to some degree. In such a setting, it becomes relevant to look into the efficiency properties of different tax portfolios – both in isolation and relative to one another (the latter of which will be done next).

Comparing the NE in the cases with factor mobility with the one under autarky, we find that the $(\kappa_1^i, \tau_1^i, 0, \tau_2^i)$ NE yields higher welfare than the NE under autarky, while this is not the case for most other Nash equilibria under factor mobility. We can state this finding as follows.

Numerical Finding 2 (The role of factor mobility)

Factor mobility does not necessarily speed up resource extraction and decrease welfare compared to autarky.

This finding is surprising because we have seen that factor mobility induces additional private income externalities that go in the same direction as the environmental externality (at least in the aggregate). We would thus expect resource extraction in period one to be higher under factor mobility. However, because of general equilibrium effects and the fact that unilateral efforts to reduce the rate of resource extraction in period one are partly offset under factor mobility by market participants abroad (through a change in world market prices), the size of the externalities can be very different, and more externalities do not necessarily imply a worse outcome.

We further observe from Table 1 that the ranking of the outcomes in the Nash equilibrium in the regimes involving factor mobility is not the same for different parameter combinations and, in particular, different elasticities of substitution. Nevertheless, there are some commonalities across combinations, which we summarize as follows.

Numerical Finding 3 (Pareto ordering of Nash equilibrium outcomes)

For the ordering of the Nash equilibrium outcomes under different tax regimes, the following holds:

1. *The $(0, \tau_1^i, 0, \tau_2^i)$ NE Pareto dominates the $(0, \tau_1^i, 0, 0)$ NE.*
2. *The $(\kappa_1^i, \tau_1^i, 0, 0)$ NE Pareto dominates the $(0, \tau_1^i, 0, 0)$ NE, the $(0, \tau_1^i, 0, \tau_2^i)$ NE and the $(0, \tau_1^i, \kappa_2^i, \tau_2^i)$ NE.*
3. *The $(0, \tau_1^i, \kappa_2^i, \tau_2^i)$ NE Pareto dominates the $(0, \tau_1^i, 0, \tau_2^i)$ NE.*
4. *The $(\kappa_1^i, \tau_1^i, 0, \tau_2^i)$ NE Pareto dominates the NE in all other regimes with factor mobility.*

The intuition for the first statement is relatively straightforward. When resource taxes can be levied both in the first and second periods, governments have higher leverage on resource use and are able to impose a higher aggregate burden on the externality-generating resource input than if they only have a resource tax at their disposal in the first period. This holds despite the fact that the second-period resource tax causes additional private income distortions. The direct positive effect of a second-period resource tax thus outweighs the associated negative effect.

The second statement shows that a tax portfolio with only first-period policies yields a strictly higher payoff than a portfolio with one or two resource taxes or a portfolio with a second-period but no first-period capital tax. The reason for this is that the capital tax in the first period is non-distortionary, as we have seen earlier, while all other taxes cause distortions.

The third statement establishes that it is better to have a capital tax in the second period in addition to a resource tax portfolio compared to an equilibrium in which only resource taxes are available. This is somewhat surprising, since the second-period capital tax is distortionary. However, it also facilitates a higher resource subsidy in the second period, which is beneficial.

The last statement shows that there is a Pareto-dominating tax portfolio. Supplementing the portfolio that includes resource taxes in both periods with a capital tax in the first period yields strictly higher welfare in equilibrium than any other regime with factor mobility. As statement 1 posits, it is better in terms of welfare to implement resource taxes in both periods, and, since the first-period capital tax is non-distortionary but facilitates a higher resource tax in the same period, statement 3 follows immediately. Together, this implies that it is always better to levy a capital tax at least in one period, preferably in the first period because of the non-distortionary character of the capital tax in that period. However, adding a capital tax in either period is not Pareto superior.

Table 1 seems to suggest that the $(\kappa_1^i, \tau_1^i, 0, 0)$ NE Pareto dominates the $(\kappa_1^i, \tau_1^i, \kappa_2^i, \tau_2^i)$ NE. However, as Table 2 in the Appendix shows, this is not true for all parameter combinations. In fact, with a very low elasticity of substitution, the additional distortions induced by period-two policies are so small that it pays off to make use of the full set of tax instruments. Nevertheless, this seems to be the exception rather than the rule.

Next, we explore the role of the elasticity of substitution between capital and resources, the results of which can be summarized as follows.

Numerical Finding 4 (The role of the elasticity of substitution)

If the elasticity of substitution between capital and resources is high,

1. *the period-one resource tax is higher and the period-one capital subsidy tends to be lower,*
2. *the welfare gains from complementing a resource tax portfolio with a first-period capital tax are higher, and*
3. *the NE under factor mobility which include a first-period capital tax are more likely to Pareto dominate the autarky NE*

when compared to a scenario in which the elasticity of substitution is comparatively lower.

The intuition for the first statement is that with a lower cross-partial derivative F_{kr}^1, i.e. a higher elasticity of substitution, a unit of resource that is lost to the other country due to the resource tax is compensated by firms through higher use of capital

(firms substitute resources with capital more strongly), which is why the government can tax resources at a higher rate while not having to worry too much about capital also being lost to the other country. Therefore, the subsidy on capital can be lower. A higher subsidy would induce firms to substitute resources with capital more strongly, which is not desired, given that the resource tax is already relatively high. Conversely, if F^1_{kr} is larger, a higher resource tax leads to a greater decrease in the demand for capital, to which the governments respond by granting a more generous subsidy to firms and levying a lower tax on resources in the first period.

The second statement follows from the first, because if resource taxes (be it in period one only or in both periods) are complemented by a first-period capital tax, the latter facilitates a higher first-period resource tax. This is beneficial since more of the environmental externality is then internalized in equilibrium. Therefore, greater welfare increases can be realized when an additional capital tax is introduced in period one if the elasticity of substitution is higher and thus allows for a higher first-period resource tax in equilibrium. Similarly, as an additional capital tax in period one is more effective when the elasticity of substitution is higher, the Nash equilibria that include a capital tax are more likely to Pareto dominate the autarky NE (statement 3). See Table 2 in the Appendix for a combination with a very low elasticity of substitution in which the autarky NE Pareto dominates the NE in all cases of factor mobility.

Finally, we examine the role of capital supply elasticity, as measured by $(\partial s/\partial \rho_2)\rho_2/s$. For this, we vary the discount factor ϵ (we could also vary the curvature of the utility function). The more impatient consumers are, the lower ϵ is. A lower ϵ implies that, in the absence of any policies, consumption is higher in the first period (and thus more resources are extracted in that period). At the same time, a higher degree of impatience implies that the consumers' savings respond more strongly to changes in ρ_2. Look at Table 3 in Appendix A.5 for two scenarios with varying ϵ (note that the equilibrium capital supply elasticity is added in the last column).

Numerical Finding 5 (The role of the capital supply elasticity)

If the equilibrium capital supply elasticity is lower, the welfare loss in the ($\kappa^i_1, \tau^i_1, \kappa^i_2, \tau^i_2$) NE is lower than with a higher capital supply elasticity.

The intuition for this finding is straightforward. Period-two policies induce additional distortions, particularly at the intertemporal consumption-savings margin. These distortions are smaller the more inelastic capital supply is in the second period.

6. Discussion

As a remedy to Green Paradox effects, Sinn (2008) proposes a supply-side policy, namely a source-based tax on capital income earned by foreign resource owners in industrialized countries. He argues that this tax will (in partial equilibrium) depress the net interest rate on reproducible capital and thus make extraction less attractive to resource owners.[30] van der Ploeg (2016) establishes that such an 'asset holding tax' imposed on oil-producing countries is only effective if a future carbon tax harms global welfare (if it is ineffective, the asset holding tax should be negative). This paper, by contrast, suggests that a supply-side policy is not necessarily the only solution to slow resource extraction. As we have seen, a demand-side policy, specifically the source-based taxation of capital investment levied on production firms, may also be able to tilt the extraction path in the right direction – even in a world in which countries compete for mobile factors of production. This policy might in fact be more realistic because policy-makers seem to be more focused on demand-side policies. In contrast to Sinn's proposal, the capital taxes here do not replace resource taxes. In fact, as illustrated in the previous section, using capital taxes *in addition* to resource taxes may Pareto dominate the solitary use of resource taxes, as is certainly the case when only period-one policies are feasible.

A natural question that arises in a two-period model is how a third period would influence the results. As it seems impossible to answer this question analytically (I would have to introduce two additional markets, a capital and a resource market in the third period, which would complicate the analysis enormously), some plausible reasoning shall be attempted here. With a third period, we would also have to model damages in the second period in order to give governments an incentive to shift resource extraction through their tax policies from the second to the third period.[31] I conjecture that the downward trend of the resource tax over time would be preserved, with the third-period resource tax being lower than the second-period tax (or the subsidy being higher). This would be in line with the well-known result from the partial equilibrium literature on resource economics that finds a declining time path for resource taxes. Most probably, the second-period tax on capital would still be positive, as would the third-period capital tax. The more taxes are added in a model with mobile factors of production, the more likely it is that additional distortions will lower equilibrium welfare. Thus, with a third period, it will most likely still be Pareto superior to levy only a first-period capital tax in addition to resource taxes in all periods.

I have assumed that the government disposes over a commitment technology (as in van der Ploeg, 2016), but this assumption is not innocuous. The open-loop Nash equilibrium where policies in the second period are feasible is time-inconsistent. Governments would want to deviate from their announced policies once the second period has arrived. In particular, they would want to levy zero taxes on second-period investment and resource use because environmental concerns are the reason for taxation in the model in the first place, and pollution that results from first-period resource use can no longer be addressed in the sec-

[30] In a two-country Ramsey growth model, Jaakkola (2012) confirms that a tax on the resource-exporting country's capital income is indeed able to achieve an efficient solution when this country does not produce goods.

[31] The natural decay and removal rate of greenhouse gases in the atmosphere would also possibly come into play.

ond period. However, it has been shown in this paper that committing oneself to period-two policies is not necessarily Pareto superior to period-one policies on its own, because additional distortions arise from the taxation of mobile inputs in the second period, even if they improve the intertemporal allocation of resources.

In the above analysis, extraction costs were assumed to be zero. Positive (and possibly convex) flow- or stock-dependent extraction costs would not change the results qualitatively in the symmetric equilibrium I focus on, but would complicate the analysis. Symmetric extraction costs would lead, for instance, to $\partial q_t^i/\partial\square = (1/2)\partial r_t/\partial\square$ for $\square = \kappa_1^i, \tau_1^i, \kappa_2^i, \tau_2^i$, implying that any tax-induced change in aggregate resource demand is met by equal changes in supply by the resource firms in all countries. The intuition is that reserves with the least extraction cost would be depleted first and at equal speed in all countries. However, with positive extraction costs, there is a second, more important change in the model that concerns Hotelling's rule. Assume, for example, that marginal extraction costs increase with the extraction of more resources. Then the price of the resource would have to rise faster in order to cover the increasing extraction costs. In a symmetric equilibrium, this would have only quantitative effects, and the qualitative results should remain the same, since all resources will have been extracted by the end of period two and no country can gain from a change in the price path of the resource.

7. Conclusion

This paper analyzed the strategic tax-setting options of governments that are competing for mobile factors of production and are concerned about the speed of resource extraction as well as revenues from mobile tax bases. I found that unilateral policies are effective in slowing down resource extraction and that Green Paradox effects arise. Furthermore, factor mobility does not necessarily aggravate transboundary pollution problems in general equilibrium, although private income externalities unambiguously move in the same direction as the environmental externality (at least in aggregate). Most importantly, governments have an incentive to make use of both resource and capital taxes if the latter are available, and they subsidize capital in the present but tax it in the future. Adding a first-period capital subsidy to the tax portfolio can increase welfare quite significantly; indeed, the higher the elasticity of substitution between capital and resources in production, the stronger this welfare effect is. In contrast to the first-period capital subsidy, the second-period capital tax is distortionary, and its use in addition to resource taxes and the capital subsidy in the first period leads to lower equilibrium welfare. The paper thus makes a differentiated case for capital taxation in the second best.

A promising avenue for future research is to incorporate into the framework of this paper revenue needs by governments that cannot be satisfied through lump-sum taxation. If revenues need to be collected from a combination of capital and resource taxes, it is less clear whether subsidies to capital in the first period and resources in the second period are still equilibrium strategies. Furthermore, it would be interesting to look into asymmetries between countries. The symmetric set-up leads to zero net resource and capital flows across borders, and so no country is able to appropriate the other country's Hotelling rents in equilibrium. An asymmetric set-up would allow for this. Finally, I have assumed inelastic resource supply. Another promising extension in future research concerns resource exploration, as in van der Ploeg (2016). In such a setting, countries might have incentives to use their tax policies in order to inhibit exploration abroad.

Appendix

A.1. Derivation of comparative statics

In the following, as well as in the main text, all functional dependencies for the production functions and thus for $\Gamma_1, \Gamma_2, \Omega$, Φ, Λ, Θ and Δ have been dropped for notational convenience. Note that the functional values of all variables are only equal in the symmetric equilibrium.

Totally differentiating first-order conditions (2) for all $i = 1, 2$ and for all $t = 1, 2$ yields:

$$F_{rr}^t dr_t^i + F_{kr}^t dk_t^i - d\tau_t^i = dp_t \ , \quad F_{kr}^t dr_t^i + F_{kk}^t dk_t^i - d\kappa_t^i = d\rho_t \ , \tag{A.1}$$

Solving equation (A.1) for dr_1^i, dk_1^i, dr_2^i and dk_2^i, we obtain:

$$dr_t^i = \frac{1}{\Gamma_t}\left[F_{kk}^t(dp_t + d\tau_t^i) - F_{kr}^t(d\rho_t + d\kappa_t^i)\right] \ , \tag{A.2}$$

$$dk_t^i = \frac{1}{\Gamma_t}\left[F_{rr}^t(d\rho_t + d\kappa_t^i) - F_{kr}^t(dp_t + d\tau_t^i)\right] \ . \tag{A.3}$$

Denoting $w^i \equiv \pi_1^i + \Pi_1^i + \psi_1^i + (1+\rho_1)\overline{k^i}$, we have:

$$dw^i = F_r^1 dr_1^i + (1 + F_k)dk_1^i + p_1(dq_1^i - dr_1^i) + dp_1(q_1^i - r_1^i) + d\rho_1(\overline{k^i} - k_1^i) \ . \tag{A.4}$$

This is needed to determine the reaction of savings to marginal changes in income induced by tax changes (see right-hand side of A.8 below). Although $dq_1^i - dr_1^i$ is indeterminate for any country $i = 1, 2$, in aggregate it holds:

$$\sum_{l=1}^{2}(dq_1^l - dr_1^l) = 0 \quad \text{and} \quad \sum_{l=1}^{2} dk_1^l = 0 \ . \tag{A.5}$$

Furthermore, in a symmetric equilibrium it holds for all $i = 1, 2$:

$$q_1^i = r_1^i \quad \text{and} \quad \overline{k^i} = k_1^i \ . \tag{A.6}$$

Totally differentiating Hotelling's rule (4) and the capital and resource market equilibrium conditions (10)–(11), using (A.4), (A.5) and (A.6), yields:

$$dp_2 = (1+\rho_2)dp_1 + p_1 d\rho_2 \ , \quad \sum_{l=1}^{2} dk_1^l = 0 \ , \quad \sum_{l=1}^{2} dr_1^l = -\sum_{l=1}^{2} dr_2^l \ , \tag{A.7}$$

$$\sum_{l=1}^{2} dk_2^l = \sum_{l=1}^{2} \frac{\partial s^l}{\partial \rho_2} d\rho_2 + \sum_{l=1}^{2} \frac{\partial s^l}{\partial w^l} dw^l = \sum_{l=1}^{2} \frac{\partial s^l}{\partial \rho_2} d\rho_2 + \sum_{l=1}^{2} F_r^1 dr_1^l + \sum_{l=1}^{2} F_k^1 dk_1^l \ . \tag{A.8}$$

Plugging in equations (A.2)–(A.3), these four equations jointly determine the market reactions $dp_1/d\square^i$, $d\rho_1/d\square^i$, $dp_2/d\square^i$ and $d\rho_2/d\square^i$ to unilateral marginal increases in $\square = \tau_1, \tau_2, \kappa_1, \kappa_2$ in country $i = 1, 2$, where a unilateral marginal increase in τ_1^i, for example, is found by setting $d\tau_2^i = d\kappa_1^i = d\kappa_2^i = 0$ and $d\tau_1^j = d\tau_2^j = d\kappa_1^j = d\kappa_2^j = 0$ for all $j \neq i$. Doing this for all 16 possible combinations, starting from a symmetric equilibrium, we get (13a)–(13d) and (16a)–(16d).

Plugging the latter equations back into (A.2)–(A.3) for the tax-increasing country i and country $j \neq i$, we obtain, after some rearrangements, equations (14a)–(15f) and (17a)–(18f).

A.2. Proof of Proposition 5

First, we have to derive the comparative statics for a marginal increase in r_1^i. Note that the production firm in country i does not choose r_1^i at the margin anymore because it receives the last unit from the government. Therefore, the equation on the left of (A.1) can be dropped for the firm in country i (but not for the firm in the other country), while the other equations in (A.1) continue to hold in i and $j \neq i$. Marginal tax rate changes in these equations are not relevant and we set them equal to zero, i.e. $d\kappa_1^i = d\kappa_2^i = d\tau_1^i = d\tau_2^i = 0 \quad \forall \quad i = 1, 2$. We can solve the resulting equations for dk_1^i, dr_2^i, dk_2^i and dr_1^j, dk_1^j, dr_2^j, dk_2^j as functions of $d\rho_1$, dp_1, $d\rho_2$, dp_2 and dr_1^i:

$$dk_1^i = \frac{1}{F_{kk}^1}\left[d\rho_1 - F_{kr}^1 dp_1\right] \ , \quad dk_1^j = \frac{1}{\Gamma_1}\left[F_{rr}^1 d\rho_1 - F_{kr}^1 dp_1\right] \ . \tag{A.9}$$

$$dr_1^j = \frac{1}{\Gamma_1}\left[F_{kk}^1 dp_1 - F_{kr}^1 d\rho_1\right] \ , \tag{A.10}$$

$$dk_2^i = dk_2^j = \frac{1}{\Gamma_2}\left[F_{rr}^2 d\rho_2 - F_{kr}^2 dp_2\right] \ , \quad dr_2^i = dr_2^j = \frac{1}{\Gamma_2}\left[F_{kk}^2 dp_2 - F_{kr}^2 d\rho_2\right] \ , \tag{A.11}$$

Plugging these equations into (A.7)–(A.8), the latter jointly determine the market reactions dp_1/dr_1^i, $d\rho_1/dr_1^i$, dp_2/dr_1^i and $d\rho_2/dr_1^i$:

$$\frac{\partial p_1}{\partial r_1^i} = -\frac{\Gamma_1[\Delta + (1+\rho_2)F_{rr}^1\Theta]}{F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta} > 0 \ , \quad \frac{\partial \rho_1}{\partial r_1^i} = -\frac{(1+\rho_2)F_{kr}^1\Gamma_1\Theta}{F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta} > 0 \ , \tag{A.12}$$

$$\frac{\partial p_2}{\partial r_1^i} = \frac{(1+\rho_2)\left[F_r^1 F_{kr}^2 + \Gamma_2 \frac{\partial s}{\partial \rho_2} - F_{rr}^2\right]}{F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta} > 0 \ , \quad \frac{\partial \rho_2}{\partial r_1^i} = \frac{(1+\rho_2)\Gamma_1[F_r^1 F_{kk}^2 - F_{kr}^2]}{F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta} < 0 \ . \tag{A.13}$$

Plugging back into (A.9)–(A.11), we obtain:

$$\frac{\partial k_1^i}{\partial r_1^i} = -\frac{F_{kr}^1[1 + (1+\rho_2)\Gamma_1\Theta]}{F_{kk}^1[F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta]} > 0 \ , \tag{A.14}$$

$$\frac{\partial k_1^j}{\partial r_1^i} = \frac{F_{kr}^1\Delta}{F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta} < 0 \ , \tag{A.15}$$

$$\frac{\partial k_1}{\partial r_1^i} = 0 \ , \tag{A.16}$$

$$\frac{\partial k_2^i}{\partial r_1^i} = \frac{\partial k_2^j}{\partial r_1^i} = \frac{(1+\rho_2)\Gamma_1\left[F_r^1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2}\right]}{F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta} \gtreqless 0 \ , \tag{A.17}$$

$$\frac{\partial k_2}{\partial r_1^i} = \frac{2(1+\rho_2)\Gamma_1\left[F_r^1 - F_{kr}^2\frac{\partial s}{\partial \rho_2}\right]}{F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta} \gtreqless 0 , \tag{A.18}$$

$$\frac{\partial r_1^j}{\partial r_1^i} = \frac{(1+\rho_2)\Gamma_1\Theta - F_{kk}^1\Delta}{F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta} < 0 , \tag{A.19}$$

$$\frac{\partial r_1}{\partial r_1^i} = -\frac{2(1+\rho_2)\Gamma_1\Theta}{F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta} > 0 , \tag{A.20}$$

$$\frac{\partial r_2^i}{\partial r_1^i} = \frac{\partial r_2^j}{\partial r_1^i} = \frac{(1+\rho_2)\Gamma_1\Theta}{F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta} < 0 , \tag{A.21}$$

$$\frac{\partial r_2}{\partial r_1^i} = \frac{(1+\rho_2)\Gamma_1\Theta}{F_{kk}^1\Delta - (1+\rho_2)\Gamma_1\Theta} < 0 . \tag{A.22}$$

Using the above comparative statics, the welfare in country i and the welfare in country j, W^i and W^j, can be differentiated with respect to r_1^i, and both evaluated at the Nash equilibrium (when all instruments are available):

$$\frac{\partial W^i}{\partial r_1^i}|_{NE} = 0 , \tag{A.23}$$

$$\frac{\partial W^j}{\partial r_1^i}|_{NE} = \frac{-2D'(r_1)(1+\rho_2)\left[2F_{kk}^2\frac{\partial s}{\partial \rho_2} - 1\right]\Gamma_1\Delta}{[\Delta+\Lambda]\left[(1+\rho_2)\Gamma_1\Theta + F_{kk}^1\left(F_{kk}^2\frac{\partial s}{\partial \rho_2}[\Omega + (1+\rho_2)F_{rr}^1] - \Delta\right)\right]} < 0 . \tag{A.24}$$

It is straightforward to show that the same proof holds also for any tax regime in which only a subset of instruments is at the governments' disposal. □

A.3. Comparative statics and Nash equilibrium under autarky

In a market equilibrium under autarky, firms' and households' first-order conditions continue to hold as before. Note, however, that all market prices in these equations are now indexed by ^{i}. The market equilibrium is described by the following conditions:

$$p_2^i = (1+\rho_2^i)p_1^i , \quad k_1^i = \overline{k^i} , \quad k_2^i = s^i , \quad Q^i = r_1^i + r_2^i . \tag{A.25}$$

Totally differentiating these conditions gives:

$$dp_2^i = (1+\rho_2^i)dp_1^i + p_1^i d\rho_2^i , \quad dk_1^i = 0 , \quad dr_1^i = -dr_2^i , \tag{A.26}$$

$$dk_2^i = ds^i = \frac{\partial s}{\partial \rho_2^i}d\rho_2^i + \frac{\partial s}{\partial w^i}dw^i = \frac{\partial s}{\partial \rho_2^i}d\rho_2^i + F_r^1 dr_1^i , \tag{A.27}$$

where w^i is defined as before and $dw^i = F_r^1 dr_1^i + (1+F_k^1)dk_1^i + p_1^i(dq_1^i - dr_1^i) + dp_1^i(q_1^i - r_1^i) + d\rho_1^i(\overline{k^i} - k_1^i)$, which simplifies to $dw_i = F_r^1 dr_1^i$ because $dk_1^i = 0, dq_1^i = dr_1^i, q_1^i = r_1^i$ and $\overline{k^i} = k_1^i$ under autarky.

Plugging in equations (A.2)–(A.3), these four equations jointly determine the market reactions $dp_1^i/d\square^i$, $d\rho_1^i/d\square^i$, $dp_2^i/d\square^i$ and $d\rho_2^i/d\square^i$ to unilateral marginal increases in $\square = \tau_1, \tau_2, \kappa_1, \kappa_2$ in country $i = 1, 2$, where a unilateral marginal increase in τ_1^i, for example, is found by setting $d\tau_2^i = d\kappa_1^i = d\kappa_2^i = 0$ and $d\tau_1^j = d\tau_2^j = d\kappa_1^j = d\kappa_2^j = 0$ for all $j \neq i$. Doing this for all 16 possible combinations, starting from a symmetric equilibrium, we get the following conditions:

$$\frac{\partial \rho_1^i}{\partial \tau_1^i} = -\frac{(1+\rho_2^i)F_{kr}^1\Theta}{\Delta} < 0 , \quad \frac{\partial \rho_1^i}{\partial \tau_2^i} = \frac{F_{kr}^1\Theta}{\Delta} > 0 , \tag{A.28a}$$

$$\frac{\partial \rho_1^i}{\partial \kappa_1^i} = -1 < 0 , \quad \frac{\partial \rho_1^i}{\partial \kappa_2^i} = \frac{F_{kr}^1(p_1 - F_{kr}^2\frac{\partial s}{\partial \rho_2^i})}{\Delta} \gtreqless 0 , \tag{A.28b}$$

$$\frac{\partial \rho_2^i}{\partial \tau_1^i} = \frac{(1+\rho_2^i)\Phi}{\Delta} > 0 , \quad \frac{\partial \rho_2^i}{\partial \tau_2^i} = -\frac{\Phi}{\Delta} < 0 , \tag{A.28c}$$

$$\frac{\partial \rho_2^i}{\partial \kappa_1^i} = 0 , \quad \frac{\partial \rho_2^i}{\partial \kappa_2^i} = \frac{F_r^1 F_{kr}^2 - \Omega}{\Delta} < 0 , \tag{A.28d}$$

$$\frac{\partial p_1^i}{\partial \tau_1^i} = \frac{\Upsilon + \Gamma_2 \frac{\partial s}{\partial \rho_2^i} - p_1 \Phi}{\Delta} < 0 \,, \quad \frac{\partial p_1^i}{\partial \tau_2^i} = \frac{F_{rr}^1 \Theta}{\Delta} < 0 \,, \tag{A.28e}$$

$$\frac{\partial p_1^i}{\partial \kappa_1^i} = 0 \,, \quad \frac{\partial p_1^i}{\partial \kappa_2^i} = \frac{F_{rr}^1 (p_1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2^i})}{\Delta} \gtreqless 0 \,, \tag{A.28f}$$

$$\frac{\partial p_2^i}{\partial \tau_1^i} = \frac{(1+\rho_2^i)(\Upsilon + \Gamma_2 \frac{\partial s}{\partial \rho_2^i})}{\Delta} < 0 \,, \quad \frac{\partial p_2^i}{\partial \tau_2^i} = \frac{(1+\rho_2^i) F_{rr}^1 \Theta - p_1 \Phi}{\Delta} < 0 \,, \tag{A.28g}$$

$$\frac{\partial p_2^i}{\partial \kappa_1^i} = 0 \,, \quad \frac{\partial p_2^i}{\partial \kappa_2^i} = \frac{p_1 \Upsilon - (1+\rho_2^i) F_{rr}^1 F_{kr}^2 \frac{\partial s}{\partial \rho_2^i}}{\Delta} < 0 \,, \tag{A.28h}$$

where $\Upsilon = F_r^1 F_{kr}^2 - F_{rr}^2 > 0$.

Plugging these equations back into conditions (A.2) and (A.3) yields (note that $k_1^i, k_1^j, r_1^j, k_2^j, r_2^j$ cannot change due to a marginal change in any of country i's tax rates):

$$\frac{\partial r_1^i}{\partial \tau_1^i} = -\frac{(1+\rho_2^i)\Theta}{\Delta} < 0 \,, \quad \frac{\partial r_1^i}{\partial \tau_2^i} = \frac{\Theta}{\Delta} > 0 \,, \tag{A.29a}$$

$$\frac{\partial r_1^i}{\partial \kappa_1^i} = 0 \,, \quad \frac{\partial r_1^i}{\partial \kappa_2^i} = \frac{p_1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2^i}}{\Delta} \gtreqless 0 \,, \tag{A.29b}$$

$$\frac{\partial r_2^i}{\partial \tau_1^i} = \frac{(1+\rho_2^i)\Theta}{\Delta} > 0 \,, \quad \frac{\partial r_2^i}{\partial \tau_2^i} = -\frac{\Theta}{\Delta} < 0 \,, \tag{A.29c}$$

$$\frac{\partial r_2^i}{\partial \kappa_1^i} = 0 \,, \quad \frac{\partial r_2^i}{\partial \kappa_2^i} = -\frac{p_1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2^i}}{\Delta} \gtreqless 0 \,, \tag{A.29d}$$

$$\frac{\partial k_2^i}{\partial \tau_1^i} = \frac{(1+\rho_2^i)(F_r^1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2^i})}{\Delta} \gtreqless 0 \,, \quad \frac{\partial k_2^i}{\partial \tau_2^i} = -\frac{F_r^1 - F_{kr}^2 \frac{\partial s}{\partial \rho_2^i}}{\Delta} \gtreqless 0 \,, \tag{A.29e}$$

$$\frac{\partial k_2^i}{\partial \kappa_1^i} = 0 \,, \quad \frac{\partial k_2^i}{\partial \kappa_2^i} = \frac{F_r^1 p_1 - \Omega \frac{\partial s}{\partial \rho_2^i}}{\Delta} < 0 \,. \tag{A.29f}$$

Also note that the above conditions are also the same for the aggregate variables in the respective period because changes in capital and resource taxes in one country do not have any influence on capital and resource use in the other country.

After plugging the comparative statics in the first-order conditions (24)–(27), we obtain equation (36).

A.4. Nash equilibrium tax rates for portfolios not analyzed in the main text

From equations (24)–(27), we obtain for the

- $(0, \tau_1^i, 0, 0)$ NE:

$$\tau_1^i = \frac{-2D'(r_1)\Gamma_1 \Theta}{\epsilon(F_{kk}^1 \Delta - (1+\rho_2)\Gamma_1 \Theta)} > 0 \,.$$

- $(\kappa_1^i, \tau_1^i, 0, \tau_2^i)$ NE:

$$\tau_1^i = \frac{2D'(r_1) F_{rr}^1 F_{kk}^2 \Theta}{\epsilon(\Gamma_2 \Theta - F_{kk}^2 \Delta)} > 0 \,, \quad \tau_2^i = \frac{-2D'(r_1)\Gamma_2 \Theta}{\epsilon(\Gamma_2 \Theta - F_{kk}^2 \Delta)} < 0 \,, \quad \kappa_1^i = \frac{2D'(r_1) F_{kr}^1 F_{kk}^2 \Theta}{\epsilon(\Gamma_2 \Theta - F_{kk}^2 \Delta)} < 0 \,.$$

- $(0, \tau_1^i, \kappa_2^i, \tau_2^i)$ NE:

$$\tau_1^i = \frac{-2D'(r_1)\Gamma_1 \left[2F_{kk}^2 \frac{\partial s}{\partial \rho_2} - 1\right]}{\epsilon\left((F_{kr}^1)^2 (1+\rho_2)\left[2F_{kk}^2 \frac{\partial s}{\partial \rho_2} - 1\right] + 2F_{kk}^1 (\Delta + \Lambda)\right)} > 0 \,,$$

$$\tau_2^i = \frac{2D'(r_1)F_{kk}^1\left[p_1F_{kr}^2 - F_{rr}^2 + 2\Gamma_2\frac{\partial s}{\partial \rho_2}\right]}{\epsilon\left((F_{kr}^1)^2(1+\rho_2)\left[2F_{kk}^2\frac{\partial s}{\partial \rho_2} - 1\right] + 2F_{kk}^1(\Delta + \Lambda)\right)} < 0\,,$$

$$\kappa_2^i = \frac{-2D'(r_1)F_{kk}^1[F_{kr}^2 - p_1F_{kk}^2]}{\epsilon\left((F_{kr}^1)^2(1+\rho_2)\left[2F_{kk}^2\frac{\partial s}{\partial \rho_2} - 1\right] + 2F_{kk}^1(\Delta + \Lambda)\right)} > 0\,.$$

A.5. Further numerical simulations

Table 2
Simulation results for $z = 0.8$, $Q^i = \overline{k^i} = 1$, $\beta_1 = \beta_2 = 0.8$, $\delta = 0.35$, $\epsilon = 0.75$.

	$\alpha_1 = \alpha_2 = -7.5$ ($\sigma_1 = \sigma_2 = 2/17$)						
	r_1^i ($p_1^{(i)}$)	r_2^i ($p_2^{(i)}$)	k_1^i ($\rho_1^{(i)}$)	k_2^i ($\rho_2^{(i)}$)	τ_1^i κ_1^i	τ_2^i κ_2^i	$D(r_1)$ W^i/W^*
Laissez-faire	.627	.373	1	.5834	0	0	.4389
	(.9192)	(1.0013)	(.0696)	(.0893)	0	0	.9111
Pareto optimum	.4634	.5366	1	.664	.6838	0	.3244
	(.4089)	(.5582)	(.0063)	(.365)	0	0	1
NE autarky	.5427	.4573	1	.6268	.3844	0	.3799
	(.6425)	(.7801)	(.0228)	(.2141)	0	0	.9787
NE $(0, \tau_1^i, 0, 0)$	.6158	.3842	1	.5887	.0549	0	.431
	(.8818)	(.9731)	(.0608)	(.1035)	0	0	.9227
NE $(0, \tau_1^i, 0, \tau_2^i)$	.6011	.3989	1	.596	.0513	-.0828	.4208
	(.9067)	(1.0185)	(.0506)	(.1232)	0	0	.9366
NE $(\kappa_1^i, \tau_1^i, 0, 0)$	.5863	.4137	1	.6037	.1937	0	.4104
	(.784)	(.8972)	(.1257)	(.1444)	-.0838	0	.9494
NE $(\kappa_1^i, \tau_1^i, 0, \tau_2^i)$	.5719	.4281	1	.6114	.1886	-.0819	.4003
	(.8067)	(.9409)	(.1103)	(.1664)	-.0758	0	.9603
NE $(0, \tau_1^i, \kappa_2^i, \tau_2^i)$	.5888	.4112	1	.5626	.0484	-.228	.4121
	(.9261)	(1.0217)	(.0432)	(.1032)	0	.1178	.9447
NE $(\kappa_1^i, \tau_1^i, \kappa_2^i, \tau_2^i)$	.5727	.4273	1	.5772	.1434	-.1993	.4009
	(.851)	(.9631)	(.0927)	(.1317)	-.0579	.1434	.9579

Table 3
Simulation results for $z = 0.8$, $Q^i = \overline{k^i} = 1$, $\beta_1 = \beta_2 = 0.8$, $\delta = 0.35$, $\alpha_1 = \alpha_2 - 0.5$ ($\Leftrightarrow \sigma_1 = \sigma_2 = 2/3$).

	$\epsilon = 0.55$							
	r_1^i ($p_1^{(i)}$)	r_2^i ($p_2^{(i)}$)	k_1^i ($\rho_1^{(i)}$)	k_2^i ($\rho_2^{(i)}$)	τ_1^i κ_1^i	τ_2^i κ_2^i	$D(r_1)$ W^i/W^*	$\frac{\partial s}{\partial \rho_2}\frac{\rho_2}{s}$
Laissez-faire	.648	.352	1	.747	0	0	.454	.555
	(.271)	(.418)	(.566)	(.541)	0	0	.502	
Pareto optimum	.240	.760	1	.677	.743	0	.168	.652
	(.088)	(.150)	(.392)	(.712)	0	0	1	
NE autarky	.376	.624	1	.728	.385	0	.263	.597
	(.125)	(.206)	(.470)	(.654)	0	0	.960	
NE $(0, \tau_1^i, 0, 0)$	.509	.491	1	.749	.184	0	.356	.570
	(.177)	(.283)	(.524)	(.602)	0	0	.871	
NE $(0, \tau_1^i, 0, \tau_2^i)$	.447	.553	1	.742	.202	-.107	.313	.580
	(.216)	(.351)	(.501)	(.626)	0	0	.917	
NE $(\kappa_1^i, \tau_1^i, 0, 0)$	.314	.686	1	.710	.515	0	.22	.617
	(.107)	(.179)	(.571)	(.679)	-.133	0	.987	
NE $(\kappa_1^i, \tau_1^i, 0, \tau_2^i)$	.253	.747	1	.684	.678	-.028	.177	.645
	(.107)	(.183)	(.540)	(.706)	-.138	0	.999	
NE $(0, \tau_1^i, \kappa_2^i, \tau_2^i)$	.442	.559	1	.691	.182	-.154	.309	.605
	(.242)	(.378)	(.498)	(.559)	0	.092	.919	
NE $(\kappa_1^i, \tau_1^i, \kappa_2^i, \tau_2^i)$	.381	.619	1	.702	.330	-.079	.266	.610
	(.173)	(.279)	(.575)	(.614)	-.103	.051	.957	
	$\epsilon = 0.75$							
Laissez-faire	.583	.417	1	1.011	0	0	.408	.290
	(.308)	(.457)	(.547)	(.486)	0	0	.877	
Pareto optimum	.275	.725	1	.935	.582	0	.192	.335
	(.138)	(.222)	(.415)	(.605)	0	0	1	

(*continued on next page*)

Table 3 *(continued)*

	$\epsilon = 0.55$							
	r_1^i ($p_1^{(i)}$)	r_2^i ($p_2^{(i)}$)	k_1^i ($\rho_1^{(i)}$)	k_2^i ($\rho_2^{(i)}$)	τ_1^i κ_1^i	τ_2^i κ_2^i	$D(r_1)$ W^i/W^*	$\frac{\partial s}{\partial \rho_2}\frac{\rho_2}{s}$
NE autarky	.394	.606	1	.981	.299	0	.276	.313
	(.185)	(.288)	(.478)	(.560)	0	0	.977	
NE $(0, \tau_1^i, 0, 0)$	.495	.505	1	.1.002	.132	0	.347	.230
	(.240)	(.365)	(.519)	(.521)	0	0	.931	
NE $(0, \tau_1^i, 0, \tau_2^i)$	.451	.549	1	.995	.140	-.095	.315	.305
	(.275)	(.423)	(.502)	(.539)	0	0	.954	
NE $(\kappa_1^i, \tau_1^i, 0, 0)$	.344	.656	1	.965	.400	0	.241	.321
	(.163)	(.258)	(.567)	(.579)	-.113	0	.992	
NE $(\kappa_1^i, \tau_1^i, 0, \tau_2^i)$	.299	.701	1	.947	.486	-.041	.209	.330
	(.172)	(.274)	(.548)	(.596)	-.119	0	.999	
NE $(0, \tau_1^i, \kappa_2^i, \tau_2^i)$	.436	.564	1	.957	.125	-.147	.305	.306
	(.305)	(.453)	(.496)	(.484)	0	.07	.960	
NE $(\kappa_1^i, \tau_1^i, \kappa_2^i, \tau_2^i)$	.397	.603	1	.960	.232	-.092	.278	.313
	(.247)	(.375)	(.555)	(.519)	-.076	.046	.976	

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